IRE Transactions

ON RELIABILITY AND QUALITY CONTROL

PGRQC-13 JULY, 1958

TABLE OF CONTENTS

Contributed Papers

Mathematical Models for Determination of Efficient Troubleshooting Routes .... A. J. Hoehn and E. Saltz 1

Computer Methods for Estimating Weibull Parameters in Reliability Studies .... J. H. K. Kao 15

Effects of Ambient Temperature on Electron Tubes .... K. Hopkinson 23

Tomorrow's Quality Demands .... H. O. Imus 29

Radio Fall Meeting
November, 1957

Progress in TV-Receiver Reliability .... E. H. Boden 36

Reliability Control Based on Multiple Sequential Feedback .... C. M. Ryerson 45

Student Announcement 57

PUBLISHED BY THE

PROFESSIONAL GROUP ON RELIABILITY AND QUALITY CONTROL

IRE PROFESSIONAL GROUP ON RELIABILITY AND QUALITY CONTROL

The Professional Group on Reliability and Quality Control is an organization, within the framework of the IRE, of members with principal professional interest in Reliability and Quality Control. All members of the IRE are eligible for membership in the Group and will receive all Group publications upon payment of prescribed fees.

Annual Fee: $2.00

IRE TRANSACTIONS®

on Reliability and Quality Control

Published by the Institute of Radio Engineers, Inc., for the Professional Group on Quality Control, 1 East 79th Street, New York 21, New York. Responsibility for the contents rests upon the authors, and not upon the IRE, the Group or its members. Individual copies available for sale to IRE-PGRQC members at $0.90, to IRE members at $1.35 and to nonmembers at $2.70.

PRINTED IN THE U.S.A.

MATHEMATICAL MODELS FOR DETERMINATION OF EFFICIENT TROUBLESHOOTING ROUTES*

Arthur J. Hoehn and Eli Saltz
Air Force Personnel and Training Research Center
Lowry Air Force Base, Colorado

The complexity of modern equipment used by industry and by the military has resulted in a serious problem of providing adequate maintenance. Of the various tasks which must be performed in maintenance of such equipment, the most difficult is troubleshooting, or the location of malfunctions. Under current methods of training and utilizing maintenance technicians, it is generally considered necessary that the technicians have a comprehensive grasp of the intricate interrelationships between the parts of equipment and the way the parts function as a system. Knowledge of these interrelationships often requires a background of high level physics and engineering. Despite this, technical schools, both in industry and in the military, have often been given the almost impossible task of providing such knowledge in short courses of a year or less.

In the face of this situation, various approaches to solution of this problem are being attempted. The present paper pertains to two methods of dealing with the problem through simplification of the troubleshooting tasks of maintenance personnel. These two approaches to simplification of maintenance requirements are (a) the design and utilization of more or less automatic testing equipments, and (b) the improved design and use of on-the-job performance supports in the form of easy-to-follow job instructions.

The reader is probably well aware of the current attention being given to the development of testing devices which permit the maintenance technician to isolate malfunctions largely by positioning switches and reading dials on a panel. Considerably less attention has been directed to the possibilities of well designed and organized job instructions or "performance guides," but it seems possible to increase the performance capabilities of relatively inexperienced mechanics and to minimize training required for many maintenance positions by utilizing detailed step-by-step troubleshooting guides. Guides of this nature, which present in detail the efficient behavior routes for locating most malfunctions in particular equipment systems, seem capable of greatly reducing the amount of information and the complexity of the concepts which the mechanics must learn and retain. They also provide a means of bypassing some of the difficult problem-solving processes which relatively few mechanics can properly accomplish.

Both in the design of more or less automatic check-out equipment and the design and construction of troubleshooting guides, there is a requirement for techniques of isolating optimal checking routes for the troubleshooting process. The identification of such optimal checking routes (i.e., statements of the optimal

---

*This report is based on work done under ARDC Project 7709, Task 37304, in support of the research and development program of the Air Force Personnel and Training Research Center, Lackland Air Force Base, Texas. Permission is granted for reproduction, use, and disposal in whole or in part by or for the United States Government. The writers wish to thank Prof. S. I. Pearson, College of Engineering, University of Colorado, for reviewing the manuscript of this paper.

selection and sequencing of troubleshooting checks) is a complex mathematical problem. Research is at present under way on possible solutions to this problem using sequential decision theory, information theory, and perhaps graph theory. However, several interim solutions can be suggested that should prove useful.

In the present paper we shall first examine the general characteristics of several interim solutions. This will include examples of how the solutions might be applied in specific, simple situations. Then we shall present a condensed table indicating the optimal conditions for use of each solution.

INFORMATION PROCESSING IN TROUBLESHOOTING

Before dealing with the specific solutions, we shall consider some of the general characteristics of the systematic troubleshooting process. This process involves selection and performance of a sequence of equipment checks. Each check serves to isolate an existing trouble into a smaller and smaller subset of the total population of N faults which could possibly occur in the equipment.

The maintenance man should, in each instance of equipment malfunction, choose and accomplish a set of checks to determine which of the possible faults is actually occurring. For any particular check to contribute to the isolation of the actual trouble, the check must lead to a reduction in the number of possible faults which remain to be considered. Results of a single informative check may eliminate from consideration as few as one of the possible faults. In some situations, a check may eliminate as many as N-1 of the possible faults. (In the latter case, a single check results in identification of the actual trouble.)

Each check in a systematic troubleshooting process is in itself a sequence of behaviors that can be made routine. However, the set of checks utilized in troubleshooting will vary from one instance of malfunction to another according to what the cause or source of malfunction is. Each relevant or informative check terminates in the noting of certain feedback information. The troubleshooter who is working without a troubleshooting guide must interpret this information and use it as a partial basis for choosing the next check. In essence, the feedback information indicates the possible faults which can now be eliminated from consideration. Thus the information restricts the areas of the equipment with which the next check should be concerned. Choice of the next check should be based on information such as:

1. The interrelationships of the components which are still possible causes of the trouble. These interrelationships will determine the amount of information that can be gotten from any given subsequent check.

2. The relative probabilities of malfunction for the possible causes.

3. The relative worktimes involved in checking the possible causes.

4. The principles for combining the above information so as to determine a most efficient next check.

Obviously in a complex equipment system the problem of processing the above information so as to come up with an optimal next check may be formidable. Ulti-

mately, specification of the behavioral content of troubleshooting guides will involve (a) specification of the behaviors involved in performing each individual check which can be made routine, and (b) specification of the sequence of checks which should be performed upon the occurrence of each possible malfunction. The second problem appears to be the more complex of the two, and it is with this problem that the present paper is concerned.

DETERMINING EFFICIENT ROUTES

Within the general concept of the troubleshooting process outlined above, there are several principles or strategies which can be followed as interim solutions. These solutions can be characterized as the worktime-probability solution, the half-split solution, and the half-split on worktime-probability solution. They were originally suggested as procedures to be developed by maintenance men on each new troubleshooting problem. However, we believe that these approaches can also be applied to the problem of programming sequences of checks for an entire equipment system.

Worktime-Probability Solution

Stolurow[2] has been most active in the development and use of this technique. It is based on knowledge of the relative frequencies of the various possible malfunctions and the time required for checking individual components. Stolurow has worked out his concept of the efficient course of action in troubleshooting in connection with reciprocating engines. According to his analysis, efficient location of defects requires the following sequence of behaviors:

1. Observing indications of engine performance, particularly dials, and interpreting them in terms of standards of normality.

2. Associating patterns of indications both with malfunction conditions and with the various faults of system components that could produce these conditions.

3. Planning a checking sequence for the underlying systems on the basis of fault probability and worktimes required in checking the possible faults.

This procedure starts with what the present writers will refer to as operational checks. These consist of determining the patterns of readings of four dials (manifold pressure, fuel flow, rpm, and TOP) for each of three power settings. The different patterns of indications point to different malfunction conditions such as "dead cylinders," "excessive oil consumption," "flooded engine," and so forth. Suppose, for example, that the pattern of dial readings is that associated with the dead cylinder malfunction condition. This malfunction may derive from different systems in the engine and from any one of several possible faults within these systems. Then the dial patterns are those indicating the dead cylinder malfunction, the trouble has thus already been isolated into a relatively small subset of the total population of possible troubles in the engine. The troubles still to be checked for in the case of the dead cylinder malfunction condition are those listed in Table I.

The problem now is, having arrived at the malfunction condition and this relatively small set of possible trouble sources, what should be the strategy

TABLE I

Dead Cylinders

Ignition System	Basic Engine
"P" lead shorted to ground	Intake valve stuck open
Open primary or secondary transformer coil	Exhaust valve stuck open
Condenser shorted to ground	Cracked cylinder head
Breaker points shorted to ground	Cracked piston head
Breaker points stuck open or closed	Faulty rings
Ignition harness leads shorted to ground or open	Worn valve seats
Dead spark plugs	Worn, burned, and pitted valves
Fouled spark plugs	Worn valve guides
Relay points in TUSC stuck together	Feathered valves
	Stretched valves

from this point in order to most efficiently isolate the one particular fault existing in the ignition system or the basic engine? Using the minimum average time per discovery of a fault as the operational criterion of the efficient course of action, the proposed procedure is to check the possible troubles associated with the malfunction in the order of increasing t/p value, where t represents the time required to check for a particular fault and p the probability of the fault. Suppose, again, that the dead cylinder dial pattern occurs.

The first decision is whether to check first the ignition system or the basic engine. Suppose also that with this pattern of dial readings there is a probability of .80 that the trouble resides in the ignition system, and a probability of .20 that it resides in the basic engine. Suppose further that the average amount of worktime involved in checking the ignition system is four hours, while the average amount of time required for checking the possible troubles in the basic engine is ten hours. The corresponding t over p values are

1. Ignition system: 4 hours/.80 = 5.00

2. Basic engine: 10 hours/.20 = 50.00

Thus, the decision would be made to check the ignition system first. The remaining set of checks to be selected would be based on the t/p values computed for each of the possible troubles which may exist in the ignition system, given the

dead cylinder dial pattern. The possible faults would be checked in the order of increasing t/p value.

The worktime-probability technique, like other troubleshooting procedures, is a general strategy whereby the population of possible faults is systematically reduced until the one existing fault has been identified. As applied to the reciprocating engine situation it determines the checking sequence only beyond the point where operational checks (readings of dials and interpretations of dial patterns) have isolated the trouble into a relatively small group of possible faults. It does not concern itself with the interrelationships between components. Rather, it proceeds as though the components were strictly independent of one another.

In evaluating the t/p solution, certain of its characteristics must be understood.

1. The solution minimizes the average time for discovering faults only when certain assumptions are met. The t/p solution eliminates only one component at a time. If a check at one component could potentially give specific information about the functioning of other components (i.e., if the components are not independent in their functioning) the t/p solution will not use this information; consequently, the t/p solution in such cases may not be an optimal one. This sharply restricts the types of equipment for which this solution is optimal.

2. The solution was developed to minimize the average time for discovering faults in a system. Even when the assumptions of the t/p solution are met the range of times necessary for fault location is likely to be very great for a complex system. Most troubles will be found very quickly. The rare troubles may take an extremely long time to find. This suggests that the t/p solution should not be used with extremely complex equipment.

3. In order to apply the t/p solution, it is necessary to have relatively reliable empirical data on the worktimes and probabilities associated with potential malfunctions. If the worktimes are equal for all checks and if probabilities are also equal, the t/p solution will break down into a random checking sequence.

Half-Split Solution

While the t/p solution suggested by Stolurow may be said to be an empirical-systematic technique, the half-split procedure suggested by Miller, Foley, and Smith[1] is a logical-systematic procedure. They have explained the half-split method by reference to a straight series chain of components such as is graphically shown in Fig. 1. However, the method appears to be applicable, at least in principle, to much more complex systems of components. The essential feature of the half-split method is "that each succeeding check is made at the midpoint of the remaining segment of the chain (or within a specified distance, in terms of the number of check points, from this point)."

Consider the system of 12 components depicted in Fig. 1, with the input to the system at the first component. The first check in this system would be made between components 6 and 7. This check, in effect, splits the system into two

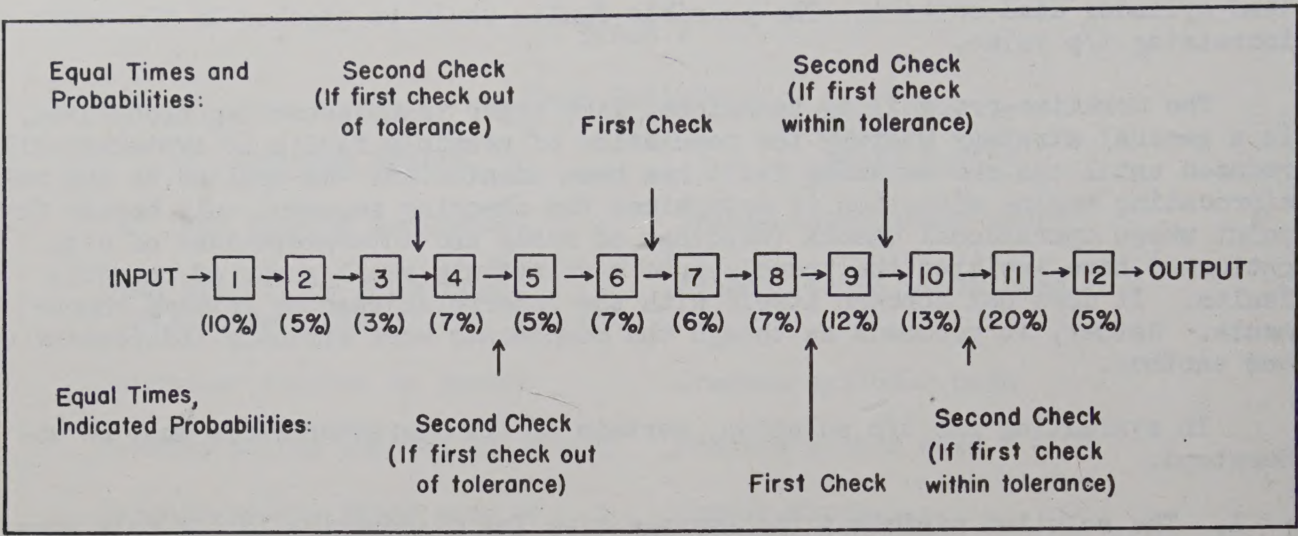

Fig. 1 - Series-chain half-split method.

subsystems and checks components 1 to 6. If the results of this check are within tolerance limits, components 1 to 6 are functioning properly and the remaining components, 7 to 12, are, in effect, split into two subsystems by checking between components 9 and 10. On the other hand, if the check between components 6 and 7 is not within tolerance, the next check would be between components 3 and 4, etc. Under certain assumptions, this technique will, as Miller, Foley, and Smith point out, result in the same number of checks to isolate a trouble, no matter what that trouble might be. In other words, this procedure minimizes the greatest number of checks necessary for identifying any malfunction.

Any 12 component system in which the components are connected in series, such as illustrated in Fig. 1, will require four checks to eliminate all components but one from consideration as possible faults. If a verification check is made on the one remaining component, a total of five checks is required to locate any trouble. This contrasts sharply with the t/p solution, which would require a minimum of one check (if the first component tested was the malfunctioning component), and a maximum of 12 checks. If the worktime and probability data were not known for this system, or if all worktimes and probabilities were equal for the 12 components, the t/p solution would result in an average of six checks to isolate a trouble, over a large number of malfunctions. Thus it can be seen that if the assumptions for the t/p solution are not met and the assumptions of the half-split solution are met, the half-split will be the more efficient procedure. On the other hand, if the probabilities and worktimes are known and are quite different for the various components, and if the components were independent (i.e., there was no flow of energy starting at one component and ending as an output from the last component), the t/p solution would be more efficient.

Usually equipment characteristics are such as to permit only an approximation of the half-split technique. Consider an illustration of an application of the half-split technique to an actual, specific piece of equipment, the C97-C landing light system. The schematic for this system is shown in Fig. 2. The troubleshooting procedure devised was based on the assumption that no more than one malfunction will be present in the equipment at a time, and largely disregards probabilities and worktimes.

The first check consists of moving the light switch to ON with the light in retract position. When this is done, nothing should happen, since limit switch D is open when the light is retracted. If the light comes on, the trouble must reside in limit switch D. If the light does not come on, the existing malfunction may be any one of the possible troubles other than the limit switch. This first check is a very inefficient one as assessed on the basis of the half-split principle, but it is very simple to notice if the light comes on, and the switch movement is necessary in order to perform the remaining checks.

Let us assume that on the first check the limit switch is found to be properly operating; that is, the light does not come on. In this case the second check is to move the right-hand extend-retract switch to extend. When this is done the right light should extend and come on. There are three possible outcomes: the light may extend and come on, the light may not extend, or the light may extend and not come on. Each of these results provides a basis for discarding from further consideration a sizable number of possible troubles. If the light extends and comes on, then the troubleshooter need no longer concern himself with those possible troubles which are associated with the light circuit or the extend circuit; if the light does not extend the troubleshooter can discard those possible troubles associated with components in the retract circuit and the light circuit; and finally, if the light extends but does not come on the troubleshooter can eliminate from further consideration the checks needed to locate troubles within the extend circuit and the retract circuit.

This check (moving the extend-retract switch to extend and noting whether the light extends and comes on), like the first check, does not exactly fit the half-split solution. It divides the population of the remaining possible

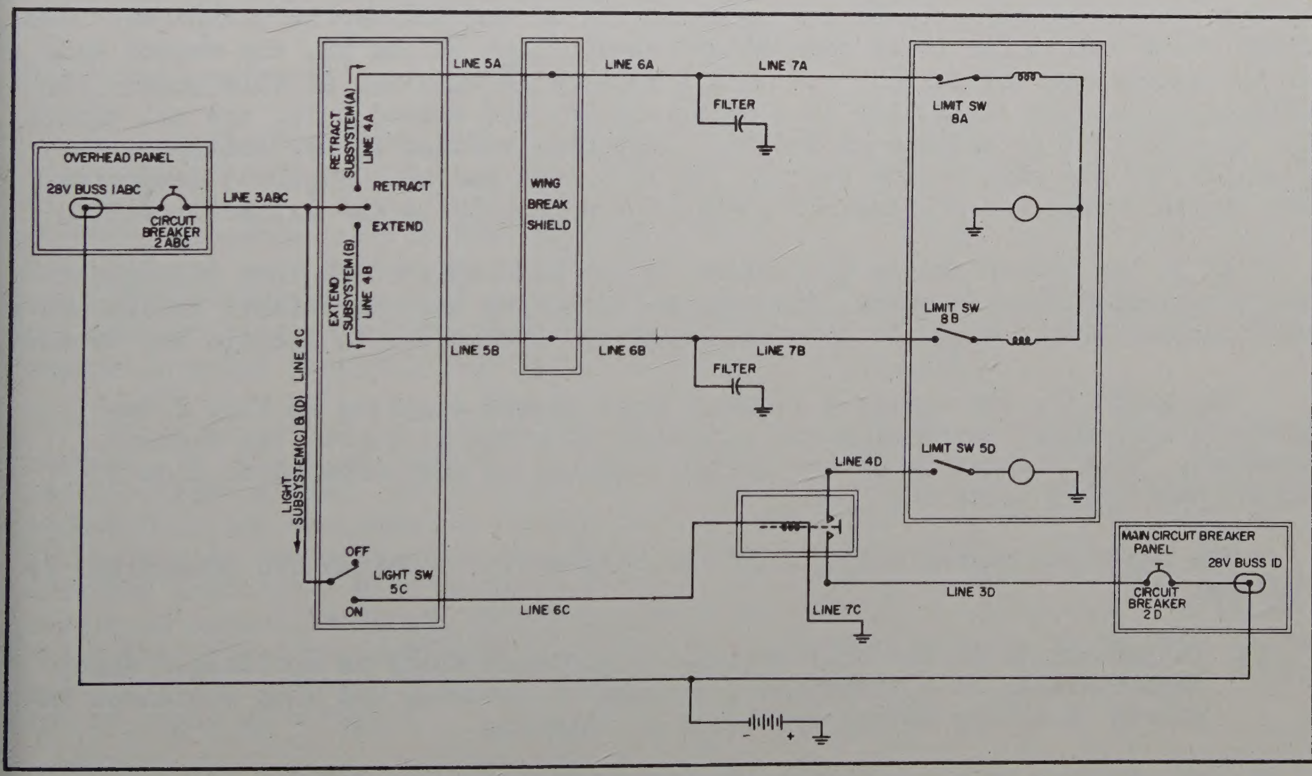

Fig. 2 - Circuit diagram of landing light system.

troubles into three unequal subsystems (the extend circuits, the retract circuit, and the light circuit) and provides the basis for eliminating troubles in two of the three subsystems. A departure from the half-split in making the second check, as well as some of the other departures which were made in the construction of the guide, is derived in part from the nature and structure of the equipment and the apparent desirability of utilizing operational checks as a point of departure in the troubleshooting procedure (a matter to be discussed more fully at a later point).

The rigorous application of the half-split technique comes in primarily after some departure from standards has been observed in performance of the operational checks. Consider, for example, the checks which follow failure of the light to extend. In this case, the troubleshooter has isolated the existing trouble into the extend circuit of Fig. 2. Note that there remain only eight possible troubles to be explored. These troubles are listed below in their serial order within the circuit.

1 ABC -- 28 v Buss
2 ABC -- circuit breaker
3 ABC -- line 3 ABC
4 B -- extend pole of extend-retract switch
5 B -- line 5B
6 B -- line 6B
7 B -- line 7B
8 B -- the extend limit switch.

The procedure by which the troubleshooter is directed to identify the trouble conforms perfectly to the requirements of the half-split technique. The first check called for is at connection between line 5B and 4B, the extend pole of the extend-retract switch. If normal voltage is obtained at this point, all components between 1 ABC, the 28 v Buss, and 4B, the extend pole, are all right; the trouble must be between 4B and 8B. If normal voltage is not obtained, the possible trouble must reside between the 28 v Buss and 4B. Figure 3 describes the complete sequence of possible checks for a trouble in the extend circuit.

If it had been possible to conform to the half-split technique throughout the troubleshooting procedure, six checks (including the operational checks and a verification check) would be both necessary and sufficient to isolate any trouble.

The guide for the complete landing light system depicted in Fig. 2 required a minimum of two checks and a maximum of seven to locate the various troubles. Thus the nature of the system resulted in some departures from a strict half-split solution.

The important characteristics of the half-split technique are summarized as follows:

1. It appears to be the only systematic approach which is applicable when probabilities of malfunction are equal or unknown, and when worktimes involved in making checks are equal or unknown.

2. It minimizes the greatest number of checks necessary for isolating any malfunction.

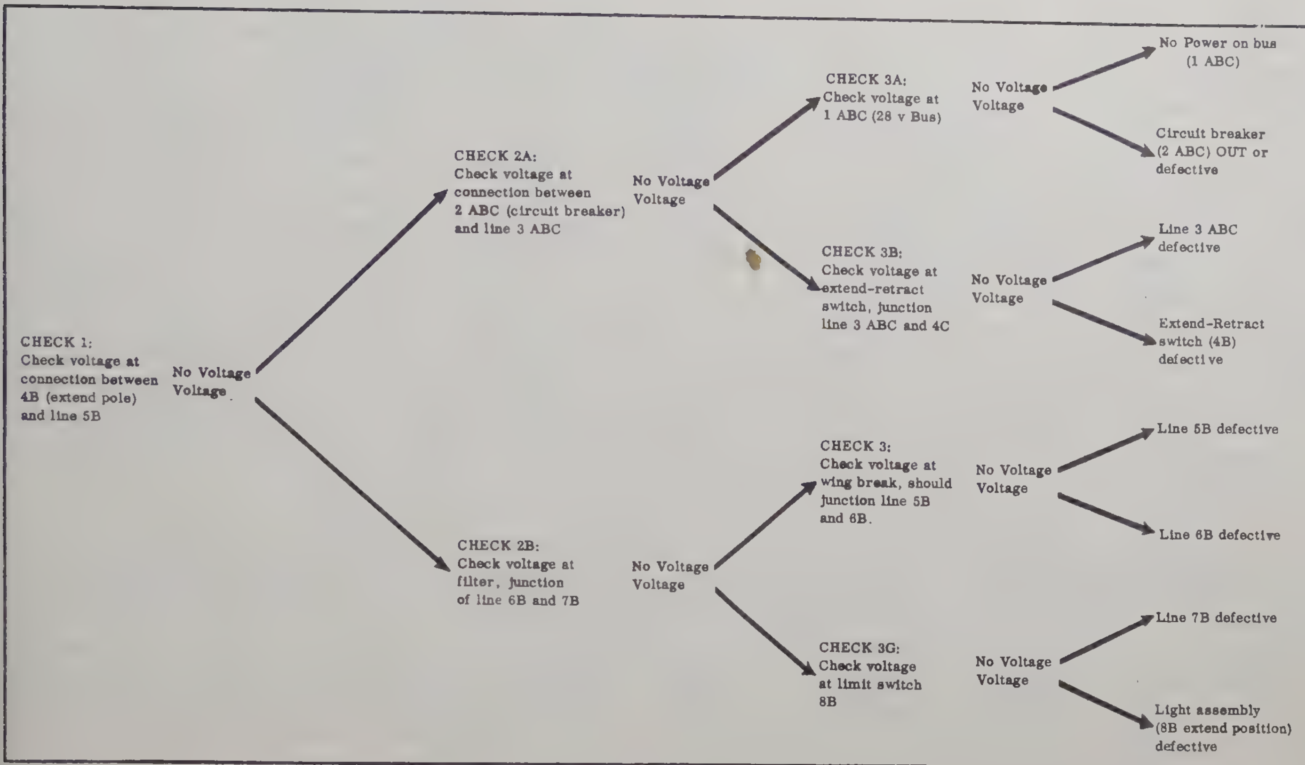

Fig. 3 - Half-split guide for extend circuit.

3. It utilizes the interrelationships between components and sequence checks. If the components are independent, this technique is not applicable.

Half-Split on Worktime-Probability Solution

In those instances in which there are interrelationships between components but worktime and/or probabilities are known and are markedly unequal, neither the t/p solution nor the half-split solution outlined above will produce an optimal checking sequence. It is possible to come closer to an optimal checking sequence by splitting on worktime or probability, or a ratio of the two. Figure 1 indicates the construction of a sequence for the case in which worktimes are equal but probabilities are divergent. A similar solution can be obtained for the instance in which probabilities are equal but worktimes differ.

Starting with a half-split solution, it is possible, at least in some instances, to obtain an improved solution by utilizing combined worktime and probability information. The worktime and probability data collected should include probability and worktime for making each of the direct checks on the possible faults during the appearance of the operational check symptom, and also the worktime associated with making each of the checks in the initial guide which was developed according to the requirements of the half-split technique. To illustrate the procedure in determining what kinds of improvements can be made in the initial guide on the basis of the newly acquired probability and worktime data, let us begin with Fig. 4.

Here the initial guide was set up on the basis of the half-split technique, and it was possible to make perfect splits in terms of number of possible

troubles so that only four checks (including the verification check) would be needed by following a half-split method. This perfect applicability of the half-split need not have characterized the initial guide in order for the present proposed procedures to be applicable. The checks in Fig. 4 are designated by letters. The check at the top of the pyramid (A) refers to the first check in the half-split process following an operational check. The checks at the base of the pyramid are checks that would be made if one were simply interested in determining whether some particular fault actually existed, or if one were verifying the inference which could be drawn from the half-split check in the box immediately above. The worktimes associated with each check are entered in the lower right-hand corner of the boxes representing the checks. Thus the worktime connected with making the first check in the half-split process (check A) would require two hours, the amount of time connected with making check F would be six hours, the amount of time required to make a direct check for fault N would be two hours, etc.

The basic probabilities are those which indicate the relative frequencies with which the various troubles are found in the system given the departure from standard noted in the superordinate operational check. These probabilities are listed in the upper left-hand corners of the checks representing direct or verification checks. Thus the probability of trouble H (or the probability of having to make check H) is .05, while the probability associated with trouble L is .20, and so forth.

It will be noted that probability values have also been entered for the checks involved in the half-split process. These have been derived from the probabilities associated with the faults. Thus the probability value for check D is the sum of the probabilities for faults H and I (.05 + .10 = .15). These probabilities, as well as those in the bottom row of checks, are the probabilities that a particular check will have to be made. Thus the probability that check E will have to be made (assuming the half-split technique is used) is .35, and the probability that check A will have to be made (given the symptom which showed up in the operational check) is 1.00, since check A would always be made when the system data given by the operational check occurred.

Having determined the p values and t values for each of the checks in the initial guide, the next step is to compute t/p values for each check. The t/p values have been entered in Fig. 1 below the respective checks. The next step is to identify those situations in which t/p values early in a checking sequence exceed one or more of those lower in the sequence. In Fig. 3 such a reversal is found in the sequence A, C, F, M. The t/p values for both check C and check F are larger than the t/p value for check M. This indicates that it may be desirable to omit checks C and F. To test this, a new set of sequences of checks has been devised to replace the right-hand side of the pyramid of checks presented in Fig. 4, and this revised set of checks is presented in Fig. 5.

Insofar as the properties of equipment to which the half-split can be applied permit, this rearrangement has been made so that there will be a continuously increasing order of t over p as one proceeds through the checking sequence. Where the results of check A initially called for going to check C, under the new arrangement one would go directly to check M, then check for fault L, and then (assuming no trouble has yet been found) go to check G and proceed as one would have done in the initial guide. The half-split on worktime-probability solution

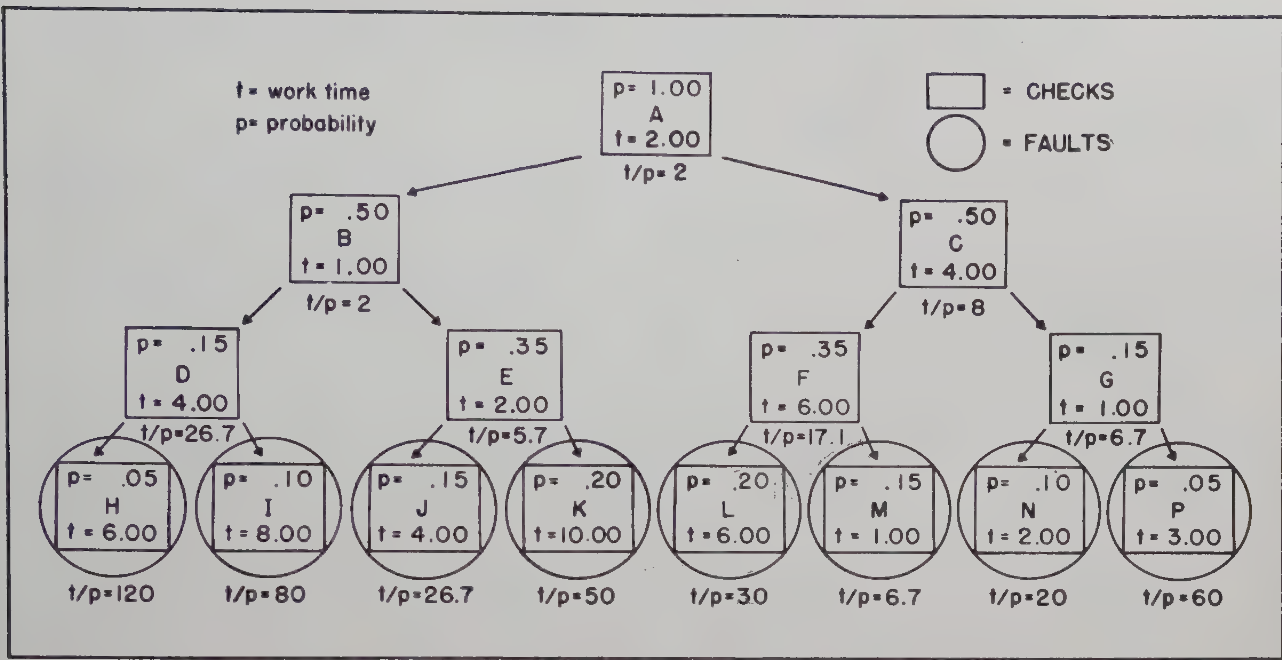

Fig. 4 - Initial guide developed using half-split and assuming equal times and probabilities. Time and probability data having been determined are now entered for revision process.

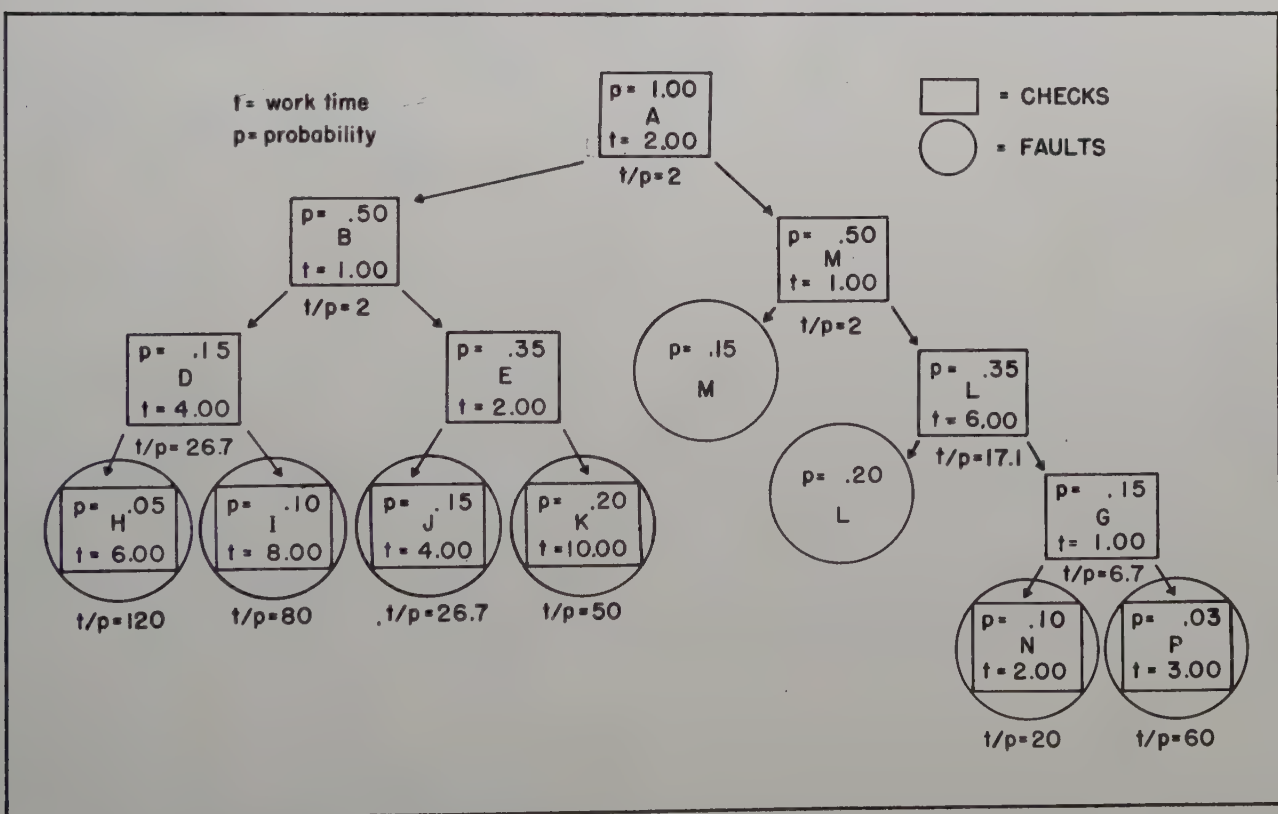

Fig. 5 - Guide revised on the basis of t/p values.

takes into account the interrelationships between components and the effects of unequal worktimes and probabilities.

Importance of Operational Checks

Note that both the procedure for the landing light system and Stolurow's procedure for reciprocating engines involved use of "operational" checks as a point of departure, and the "half-split" or probability-worktime principles were applied only beyond that point where some departure from standards was noted in an operational check. What is the nature of operational checks and why do they serve as a useful set of initial checks?

Operational checks are like other checks in the troubleshooting procedure in that they are operations that can be made routine concerned with determining conformance to, or type and/or degree of departure from standards. They differ from other checks primarily in that they ordinarily involve manipulations of controls used in actual operation of the equipment and observation of readily available feedback information of the type which an operator would note in utilization of the equipment. Also, a complete set of operational checks for a particular piece of equipment is a means of determining whether the total equipment is operating properly.

More specifically, they provide information as to whether the equipment is operating properly (or whether some fault is present), and they permit at least a partial isolation of the fault if one is present. As an illustration of these features of operational checks, consider again the landing light system. Here the operational checks involve a very simply performed set of operations: moving switches and determining whether the landing lights go on and off and whether they extend and retract. If one of these standard operational outputs is not achieved while others are, one can deduce that the malfunction resides in the subset of the total population of possible troubles which underlies that operational output which, on this occasion, is not being obtained.

In summary, operational checks are like other checks in the troubleshooting process in that they are sequences of operations that can be made routine and contribute to isolation of a fault. They are usually relatively easy to perform. Perhaps even more important from the standpoint of their value as a point of departure in the troubleshooting process, the deviations from standards noted in operational checks tend to be those which are noted in actual operation or utilization of the equipment and are the deviations commonly called symptoms. Where the symptom information furnished by the operators is sufficiently reliable, organization of the eventual troubleshooting directions with the operational checks as points of departure will permit optimum utilization of the reported symptom information. In situations where the symptom information reported by operators is not sufficiently accurate or complete, the checkout procedure provides a simple, systematic, and comprehensive scheme for verifying or identifying the symptom information.

It should not be inferred from what has been said that existing operational checking procedures are necessarily the most efficient that could be devised for purposes of troubleshooting or even for determining whether a trouble does or does not exist in a piece of equipment. At least in some instances it is probable that more efficient checkout procedures (complete sets of operational

checks) could be identified. From the standpoint of troubleshooting, an effective checkout procedure should require a minimum of time and other resources, determine whether or not the total equipment is working properly, and provide a basis for isolating any trouble which may exist, down to some relatively small area of the equipment. Insofar as possible, the operational checks would conform to the demands of the half-split process, although with existing equipment it is unlikely that any close conformance to it will be possible.

This is admittedly a considerable simplification of the problem of identifying optimum operational checks, and research is needed to determine a methodology for selecting operational checks and their sequences. Nevertheless, it is believed that existing operational checking procedures are often reasonably adequate and can form a useful point of departure in troubleshooting activity. If this is the case, determination of the behavioral content of a troubleshooting guide can be anchored on one end by knowledge of the operational checks and the decisions which the operational checks make possible, and on the other end by the population of possible faults and their probabilities of occurrence.

Feasibility of Obtaining Worktime and Probability Data

In actual practice it is probably true that the most usual situation is that in which some knowledge is available by which to gauge relative probabilities of the various faults and worktimes associated with the various checks. If actual empirical data have not been obtained through maintenance of appropriate records, it may be possible to make estimates of the relative probabilities and worktimes associated with the various possible troubles on the basis of past experience with other similar equipment. Of course, it is still a moot question as to the extent to which probabilities and worktimes can be accurately estimated before the equipment is put into actual use. It would be worthwhile to determine the accuracy of such estimates on a sample of various kinds of equipment as a basis for determining whether to devise a troubleshooting procedure using these estimates. Should such estimates prove accurate, the date of constructing optimally useful guides might be moved up to the point where such guides might be available when the equipment first comes into operational use. Otherwise, interim guides may be necessary before the appropriate data become available.

It should be pointed out that the use of worktime data is a complex affair, since there are dependencies between worktimes. Taking the head off an engine involves long worktime; checking the valves also involves long worktime. However, the choice between removing the head and checking the valves cannot be made on the basis of the absolute time to do each, but must take into account the fact that the head must be removed before the valve can be checked. If the probability of head malfunction were low and of valve malfunction high, it might still be more efficient to check the head before checking the valve as the additional time involved in checking the head is small, once the head is removed. If some checks are extremely crucial to a troubleshooting guide, and if the guide is present before the equipment is finally in production, engineering might reduce the worktime for these particular checks.

Selecting Appropriate Solution

Characteristics of the equipment and the amount of worktime-probability information available will determine which of the above solutions to use in a spe-

TABLE II

Criteria for the Selection of Appropriate T - S Solutions

Model	Criteria
1. Worktime-probability	1. Little relationship between components. 2. Either or both worktime and probability data known.
2. Half-split	1. Relationship exists between components. 2. Neither worktime nor probability known. 3. Or even if worktime and probability are known, if criterion is lowest maximum number of checks.
3. Half-split on worktime-probability	1. Relationship exists between components. 2. Either or both worktime and probability are known.

cific instance. Table II lists the factors to be considered in making a solution on a particular type of solution. These constitute a rough set of rules which are not infallible. On the other hand, these rules should, on the average, prove to be more efficient than a chance determination of an appropriate solution.

As was stated earlier in this paper, the proposed solutions are only interim solutions. Research for determining more precise solutions is being carried on under sponsorship of the Air Force Personnel and Training Research Center.

BIBLIOGRAPHY

1. Miller, R. B., Foley, Jr., J. D., and Smith, P. R.: "Systematic Trouble-shooting and the Half-Split Technique." Technical Report 53-21, Human Resources Research Center, Lackland Air Force Base (July 1953).

2. Stolurow, L. M., Bergum, B., Hodgson, T., and Silva, J.: "The efficient course of action in 'troubleshooting' as a joint function of probability and cost." Ed. and Psychol. Meas., 15:462-477 (1955).

COMPUTER METHODS FOR ESTIMATING WEIBULL PARAMETERS IN RELIABILITY STUDIES

John H. K. Kao*
Cornell University
Ithaca, New York

Summary -- In an earlier paper[3] which appeared in this Transactions, the author showed in the appendixes two methods of estimating the shape and scale parameters of a Weibull distribution from a set of life testing data. They are: (I) the method of least squares for the transformed data, and (II) the method of maximum likelihood for ungrouped data. It was pointed out that since the method of least squares was the simpler of the two, it could be used as a first approximation for getting the maximum likelihood estimate which involves solving, by trial and error, two simultaneous transcendental equations. As a measure of simplifying the computation of the analysis, the author suggested fixing the shape parameters at $m = 1.7$, when studying the reliability of electron tubes. This value of $m = 1.7$ was an average value based upon the life experience data, then available to the author, of some 2,000 electron tubes.

With the wide popularity and availability of electronic computer, the above simplifications are no longer necessary, though still desirable for reasons explained in the text. This paper describes two additional methods for which the computers are almost indispensable. They are: (III) the method of maximum likelihood for grouped data, and (IV) the method of minimized chi-squares. For the sake of discussion, the two previous methods (I and II) are briefly reviewed. As an illustration, the life testing data for five lots of some 400 electron tubes by a large tube manufacturer are treated by all four methods of estimation. Comparisons are made on the results and merits of these methods.

TYPES OF LIFE TESTING DATA

For economic and other considerations, life tests are usually truncated in one of the following two ways:

Item truncation. In this case the life test is stopped when rth item of the n items originally placed on life test fails. Here r is any integer and $1 \leq r < n$. For example, we may have 20 items placed on life test initially and we may choose to stop the test as soon as we have had 16 failures or 80 per cent of the original number.

With the item truncation, the life testing data usually consist of the precise failure ages of items under test. That is, the observations, x_i (i = 1, 2,

With the item truncation, the life testing data usually consist of the precise failure ages of items under test. That is, the observations, x_i ($i = 1, 2, \ldots, r$) are such that $0 < x_1 \leq \ldots \leq x_r < \infty$, where x_i is the exact failure age of ith item. There are practical situations where this type of data is available. For

*Assistant Professor in engineering statistics and quality control, Department of Industrial and Engineering Administration, Sibley School of Mechanical Engineering, Cornell University.

example, when life testing antifriction bearings it is often possible to note the noise level of a bearing in order to decide whether or not a bearing has failed and, hence, the "exact" failure age of items recorded. These single ordered observations are called ungrouped life testing data.

Time truncation. In this case the experimenter wishes to stop the life test when a certain time z_k has elapsed, regardless of the number of failures which have occurred. Here z_k is any real number and $0 < z_k < \infty$. For example, we may again have 20 items placed on life test initially and we may choose to stop the test when an elapsed time of 5,000 hours has been reached, regardless of whether or not we have had 16 failures.

With the time truncation, the life testing data will consist of some conveniently chosen times of inspection, z_j ($j = 1, 2, \ldots, k$), and the frequencies, f_j, which are the number of failures occurred between times z_{j-1} and z_j, where $z_{j-1} < z_j$. That is, the observations are pairs of numbers z_j, f_j (for $j = 1, 2, \ldots, k$). For example, with items such as electron tubes, where the failure criterion involves a number of electrical and mechanical tests, it is natural to record the life testing data in this fashion. These paired ordered observations are called grouped life testing data.

In view of the above discussion we see that the ungrouped life testing data are associated with item truncation and grouped life testing data with time truncation. However, for purposes of analysis, we sometimes require data of the type just opposite to the above convention. This, of course, involves some approximations. For example, in life testing electron tubes where data are normally in the grouped form, $z_1f_1, z_2f_2, \ldots, z_kf_k$, we may convert the data into the ungrouped form, $x_1, x_2, \ldots, x_r$, by assuming (a) all f_j items which failed between z_{j-1} and z_j have a failure age of $x_j = \frac{1}{2}(z_{j-1} + z_j)$, and (b) the last inspection time z_k equal to x_r. The first approximation is customarily used in statistical practice whenever the intragroup information is unavailable. The second approximation involves assuming that the last truncated failure occurs precisely at x_r. Both approximations are not unreasonable if $(z_j - z_{j-1})$ are small for all j. On the other hand, if the data are in the ungrouped form, in order to convert them into grouped form, all that is necessary is to properly group them. By so doing, of course, some intragroup information in the data would be lost. Again a good practice to follow is to choose the time of truncation $z_k = x_r$, as before.

These ways of truncating the life testing data also serve the purpose of defining some of the notations of life testing data which were used previously[2-4] and are to be used again here.

PREVIOUS METHODS OF ESTIMATION

I. The Method of Least Squares on Transformed Data

Denote by $F(x) = 1 - e^{-\frac{x^m}{x_o}}$ the Weibull cumulative distribution with shape parameter m and scale parameter x_o, where x is the failure age of items in some convenient time unit. $F(z_j)$ then gives the probability that any item under test will fail on or before time z_j. Taking the natural logarithm of $F(z_j)$ twice, we get

$$\ln \ln \frac{1}{1 - F(z_j)} = -\ln x_o + m \ln z_j \,. \tag{1}$$

Using the grouped life testing data of the form: z_j, f_j, (for $j = 1, 2, \ldots, k$), denote $F_j = \sum_{i=1}^{j} f_i$, which are the cumulative number of failures occurring on or before time z_j. Let S_j be the number of survivals still remaining at time z_j. Clearly $F_j + S_j = n$ for all j. It can be shown that F_j/n is an unbiased minimum-variance estimate of $F(z_j)$. Hence $(n - F_j)/n = S_j/n$ is an unbiased minimum-variance estimate of $1 - F(z_j)$. Substituting this in Eq. (1), we get

$$\ln \ln (n/S_j) = -\ln x_o + m \ln z_j, \; j = 1, 2, \ldots, k \, , \tag{2}$$

which is in terms of the grouped data z_j; f_j, and may be used for estimating m and x_o (through $\ln x_o$) by the usual method of least squares.

Since Eq. (1) is a straight line on log vs. log-log paper, a quick and easy way of getting a pair of estimates is to plot the k points given by Eq. (2) on log vs. log-log paper. A straight line passing through these points fitted by eye gives the y-intercept (in log-log direction) as the estimate of $\ln x_o$ and the slope as the estimate of m.

II. The Method of Maximum Likelihood for Ungrouped Data

Denote the Weibull density function by

$$dF \doteq f(x) = \frac{m\, x^{m-1}}{x_o} e^{-\frac{x^m}{x_o}} ,$$

then the likelihood function for ungrouped life testing data, $x_1, x_2, \ldots, x_r$, from a sample of size n where $r \leq n$ is

$$L = \frac{n!}{(n-r)!} \left(\frac{m}{x_o}\right)^r \prod_{i=1}^{r} x_i^{\,m-1} \exp\left\{\frac{-1}{x_o}\left[\sum_{i=1}^{r} x_i^{\,m} + (n-r) x_r^{\,m}\right]\right\} . \tag{3}$$

By putting the first partial derivatives of $\ln L$ with respect to m and x_o equal to zero, we get

$$x_o = \frac{1}{r}\left[\sum_{i=1}^{r} x_i^{\,m} + (n-r)\, x_r^{\,m}\right] \tag{4}$$

$$x_o = \frac{\sum_{i=1}^{r} x_i^{\,m} \ln x_i \overset{*}{+} (n-r)\, x_r^{\,m} \ln x_r}{\frac{r}{m} + \sum_{i=1}^{r} \ln x_i} \tag{5}$$

*In the work referred to in reference 3 of the Bibliography, this sign was misprinted as a minus sign.

which, if solved simultaneously by trial and error, give the so-called maximum likelihood estimates of the parameters m and x_o for ungrouped data. The above reviews the two methods already discussed.[2-4]

NEW METHODS OF ESTIMATION

III. The Method of Maximum Likelihood for Grouped Data

For the grouped life testing data of the form z_j, f_j ($j = 1, 2, \ldots, k$), denote by p_j the probability that any item will fail in the time interval z_{j-1} to z_j, then

$$p_j = F(z_j) - F(z_{j-1}) \text{ and, in particular,}$$

$$p_1 = F(z_1) - F(0) = F(z_1), \text{ and}$$

$$p_{k+1} = F(\infty) - F(z_k) = 1 - F(z_k) . \tag{6}$$

Substituting $F(z_j) = 1 - e^{-\frac{z_j^m}{x_o}}$, we get

$$p_j = e^{-\frac{z_{j-1}^m}{x_o}} - e^{-\frac{z_j^m}{x_o}} ,$$

$$p_1 = 1 - e^{-\frac{z_1^m}{x_o}} , \text{ and}$$

$$p_{k+1} = 1 - \sum_{j=1}^{k} p_j = e^{-\frac{z_k^m}{x_o}} . \tag{7}$$

The likelihood function is given by Cramér (1, p. 318) as the following multinomial distribution:

$$L' = \frac{n!}{\prod_{j=1}^{k+1} f_j} \prod_{j=1}^{k+1} (p_j)^{f_j} \qquad \text{where}$$

$$\sum_{j=1}^{k+1} f_j = n \quad \text{and} \quad \sum_{j=1}^{k+1} p_j = 1 . \tag{8}$$

In order to maximize L' with respect to m and x_o it is sufficient to maximize ln L as follows:

$$L = \prod_{j=1}^{k+1} (p_j)^{f_j} = \left(1 - \sum_{j=1}^{k} p_j\right)^{n-\sum_{j=1}^{k} f_j} \cdot \prod_{j=1}^{k} (p_j)^{f_j} . \tag{9}$$

Substituting Eq. (7) in Eq. (9), we get

$$L = e^{\frac{-z_k^m}{x_o}} (n - \sum_{j=1}^{k} f_j) \cdot \prod_{j=1}^{k} \left[e^{\frac{-z_{j-1}^m}{x_o}} - e^{\frac{-z_j^m}{x_o}} \right] f_j \; . \tag{10}$$

Taking the natural logarithm of Eq. (10), we get

$$\ln L = \frac{-z_k^m}{x_o} (n - \sum_{j=1}^{k} f_j) + \sum_{j=1}^{k} f_j \ln \left[e^{\frac{-z_{j-1}^m}{x_o}} - e^{\frac{-z_j^m}{x_o}} \right] . \tag{11}$$

In the above, z_j, f_j ($j = 1, 2, \ldots, k$) are known, hence $\ln L$ is a surface over the $m - x_o$ plane. The pair of m and x_o, say m^* and x_o^*, which maximizes $\ln L$ (and hence L) is called the maximum likelihood estimate of the Weibull parameters for grouped data. In previous works[2,3] formulas were also indicated for obtaining the maximum likelihood estimate -- $\widehat{m}$ and $\widehat{x}_o$ in the case of grouped data by modifying Eqs. (4) and (5). The estimates m^* and x_o^* here by the present method will be different from $\widehat{m}$ and $\widehat{x}_o$. But the difference is expected to be small. It is difficult to differentiate either Eq. (10) or Eq. (11) with respect to m and x_o, hence the trial and error method must be used to maximize them. With an electronic computer such as IBM 650, either one of these equations may be programmed for maximization with respect to m and x_o in order to obtain m^* and x_o^*.

IV. The Method of Minimized Chi-Squares for Grouped Data

Following the definition of p_j given by Eq. (6), np_j (for $j = 1, 2, \ldots, k+1$) will be the expected number of failures between inspection time z_{j-1} and z_j. If p_j were known from other considerations, then, for large n, provided that $np_j \geq 5$ and $k+1 \geq 5$, the following quantity has approximately a chi-square distribution k degrees of freedom (5, p. 167):

$$\lambda^2 = \sum_{j=1}^{k+1} \frac{(f_j - np_j)^2}{np_j} = \sum_{j=1}^{k+1} \frac{f_j^2}{np_j} - n \; . \tag{12}$$

The last member of Eq. (12) is obtained by the relationship:

$$\sum_{j=1}^{k+1} p_j = 1 \quad \text{and} \quad \sum_{j=1}^{k+1} f_j = n \; .$$

However if p_j are unknown and their values depend on the paremeters of $F(x)$ to be estimated from the data, Eq. (12) still has approximately a chi-square distribution, provided that the unknown parameters are replaced by their maximum likelihood estimates and that the degrees of freedom are reduced by one unit for each parameter estimated (5, p. 170). The fact that Eq. (12) remains to be approximately a chi-square variable, regardless of whether or not p_j are known, indicates that it is completely independent of the form of the underlying mortality distribution $F(x)$ assumed. For this reason Eq. (12) may be used as a criterion for

judging the goodness of fit between the data and the estimated distributions (1, p. 425). Of course, the smaller the λ^2-value the better the fit. A large λ^2-value may be thought of as poor fit and an ordinary chi-square table may be used to reject the goodness of fit at some preassigned level of significance.

As a matter of fact, if the form of a Weibull distribution is assumed as the general failure-age distribution, Eq. (12) provides a further method of estimating the Weibull parameters. The method consists of minimizing Eq. (12) with respect to m and x_o. Of course, we may alternatively minimize $\sum_{j=1}^{k+1} f_j^2/p_j$ which for a Weibull distribution is

$$\left(n - \sum_{j=1}^{k} f_j\right) e^{\frac{z_k^m}{x_o}} + \sum_{j=1}^{k} f_j \Big/ \left[e^{\frac{-z_{j-1}^m}{x_o}} - e^{\frac{z_j^m}{x_o}} \right]. \tag{13}$$

In the above, z_j, f_j ($j = 1, 2, \ldots, k$) and n are known life testing data and the parameter m and x_o are to be estimated. The pair: $\check{m}$ and $\check{x}_o$ which minimizes Eq. (13) is called the minimized λ^2 estimate of the Weibull parameters for grouped data. Again an electronic computer is indispensable for the minimization of Eq. (13) which is too tedious otherwise.

COMMENTS ON ALL FOUR METHODS OF ESTIMATION

Method I, employing the least squares on the transformed data, has little theoretical justification. This is because of the fact that the least squares approach there does not necessarily guarantee the "best" fit of the raw data in the Cartesian scale. The practical value of this method lies in the fact that it is simple. That is, if either transformed data or log vs. log-log paper is used, an approximate estimate of Weibull parameters may be obtained by simply plotting the data and estimating them by eye. This graphical solution is, in general, not too far off from the theoretically better estimates provided by Methods II, III, and IV.

Method II is the best among the four, if the data are naturally ungrouped (e.g., ball-bearing life testing). This method utilizes the precise failure age of each item failed in providing the estimates. However, this method would also give a reasonably good estimate with data in the grouped form (e.g., electron tube testing), provided the grouped raw data is such that the number of failures per inspection period is small. In programming this method on an electronic computer, Newton's approximation may be used for solving the two simultaneous transcendental equations. This procedure converges very rapidly, especially if the graphical solution obtained by Method I is fed into the computer as the initial trial.

Method III is the best if the life testing data are originally obtained in grouped form and for some reason or other the group sizes are large; i.e., the inspection periods are long so that the number of failures per inspection period are not small. We have actually encountered such a case in analyzing a large amount of life testing data of electron tubes under the U. S. Army Signal Corps Contract No. DA36-039-sc-42524, conducted at GE in Owensboro, Kentucky. When

this is the case, Method III is preferable because Method II will be relatively poor due to severe approximations. Actually, Methods II and III are theoretically equivalent; they both provide the maximum likelihood estimates of the Weibull parameters. Because of the difficulty in Method III for an analytical solution, it will take more computer time than Method II. The computer program for Method III will generally consist of a series of trials in the parameter space of desired accuracy which converges rather slowly even when a two-stage procedure of coarse and fine mesh is chosen.

Although Method IV is the best from the standpoint of λ^2-criterion for goodness of fit, it places a restriction on the data by requiring $np_i \geq 5$ and $k+1 \geq 5$ and in addition it lacks some of the desirable properties of maximum likelihood estimates (e.g., invariance, sufficiency, efficiency). As in the case of Method III, it is also only appropriate for the grouped life testing data. With some modifications shown by Cramér (1, p. 426) it can be made theoretically equivalent to Method III (a modified minimized λ^2 estimate shown by Cramér is identical to a maximum likelihood estimate). The computer program for Method IV is essentially the same as that of Method III; i.e., optimization in the selected parameter space. Both programs can be shortened considerably in the number of iterations if the graphical solution by Method I is fed into the computer as the initial trial.

AN EXAMPLE

Table I shows the grouped life testing data of five lots of electron tubes from a large tube manufacturer from an early report.[4] Because of the limitations in the minimized λ^2 method and because of our desire to compare these four methods of estimation, the data are regrouped so that $k+1 \geq 5$ and hence $np_j \geq 5$. Table II shows the estimate of Weibull parameters by the four methods. The goodness of fits by the λ^2-criterion are in all cases excellent, as indicated by the computed probability P's (by/curvilinear interpolation) which are to be interpreted as follows. Implicitly we have conducted a series of statistical tests

---

TABLE I

Life Testing Data
(number of failures f_j between inspection times
z_{j-1} and z_j for five tube lots)

Tube Lots	No. of Inspection Periods, k	Inspection Time, z_j (thousands of hours) 1	2	3	4	5	6	7	8	9	10	Survivals f_{k+1}	Totals $n = \sum_{j=1}^{k+1} f_j$
1	10	3	7	18	11	11	7	8	8	6	3	7	89
2	9	-	3	5	6	4	9	5	7	7	9	70	125
3	8	-	4	3	5	3	3	-	5	4	3	33	63
4	4	5	9	-	13	6	-	-	-	-	-	25	58
5	4	3	5	-	15	3	-	-	-	-	-	6	32

TABLE II

Estimate of Weibull Parameters and Computed Chi-Squares by Various Methods of Estimation

Tube Lots	d.f.	I				II				III				IV			
		m	x_0	λ^2	P	m	x_0	λ^2	P	m	x_0	λ^2	P	m	x_0	λ^2	P
1	8	1.85	26.31	6.78	.56	1.74	21.3	6.35	.61	1.74	21.1	6.20	.63	1.74	21.106	6.19	.63
2	7	1.89	131.6	2.94	.89	1.83	116.1	3.16	.87	1.85	122.5	3.12	.87	1.85	119.75	3.09	.88
3	6	1.36	36.6	1.77	.94	1.38	36.74	1.77	.94	1.35	35.0	1.70	.94	1.39	37.875	1.67	.95
4	2	1.66	13.7	3.41	.19	1.37	10.58	0.59	.74	1.31	9.75	0.52	.76	1.31	9.70	0.52	.76
5	2	1.54	7.24	1.89	.39	1.86	11.4	1.00	.60	1.82	10.88	0.97	.61	1.82	11.0	0.97	.61

of hypothesis that the tube lots are samples taken from the respective Weibull distributions with parameters as estimated here. Using a significance level of 5 per cent we accept the hypothesis if $P \geq 0.5$. The degrees of freedom are $(k - 2)$ since two parameters are estimated.

Note the improvement of goodness of fit as indicated by the increasing values of P's. Clearly Methods III and IV are more refined in this respect.

ACKNOWLEDGMENT

The author wishes to thank Messrs. William Y. Stevens and Birger Lövgren for programming these methods on an IBM 650 magnetic drum computer and Messrs. John D. Berry and Birger Lövgren for computation at the Cornell Computing Center. The work is done under U. S. Army Signal Corps Contract DA36-039-sc-64646, under the directorship of Prof. G. C. Dalman.

BIBLIOGRAPHY

1. Cramér, H: "Mathematical Methods of Statistics." Princeton, Princeton University Press, 1951.

2. Kao, H. K.: "Quantifying the Life-Quality of Electron Tubes with the Weibull Distribution." Technical Report No. 26, School of Electrical Engineering, Cornell University, Ithaca, N. Y. (Nov. 1955).

3. Kao, H. K.: "A new life-quality measure for electron tubes." <u>Trans. IRE</u>, PGRQC-7, pp. 1-11 (Apr. 1956).

4. Kao, H. K.: "The Weibull Distribution in Reliability Studies of Electron Tubes." Technical Report No. 33, Research Report EE 343, School of Electrical Engineering, Cornell University, Ithaca, N. Y. (Sept. 1957).

5. Hoel, P. G.: "Introduction to Mathematical Statistics," 2nd ed. New York, John Wiley and Sons, 1954.

EFFECTS OF AMBIENT TEMPERATURE ON ELECTRON TUBES

K. Hopkinson
Ministry of Supply
Royal Radar Establishment
Great Malvern, Worcs., England

During an investigation into the effects of high temperature and high altitude operation on the life of electron tubes I had occasion to refer to an article which was published in the 1956 IRE National Convention Record, Part 6. This article formed part of a section headed "A Basic Study of the Effects of Operating and Environmental Factors on Electron Tubes" and was called "The Effects of Ambient Temperature" by Paul F. Barnett.

Mr. Barnett gives data on the survival rates of five types of electron tubes, namely 6005, 6J6W, 5654, 5726, and 5670. Lots of 200 valves were assembled for each test with all approved manufacturers' products being represented. Life tests were carried out under JAN specification conditions at various ambient temperatures, and measurements of characteristics were made at the life test temperature. The following tables of results have been compiled from the survival rate curves given in the article and there may be some inaccuracies in reading from the published curves.

TABLE I

	Lot No.	Ambient Temp. (°C)	Bulb Temp. (°C)	Survival Per Cent Zero Hours	250 Hours	500 Hours	1,000 Hours
Tube type 5670	1	Room	100	98	95	95	90
	2	100	115	95	95	95	88
	3	175	186	93	93	93	93
	4	250	261	95	77	74	72
Tube type 6J6W	1	Room	110	98	98	98	90
	2	100	134	98	95	93	90
	3	175	201	98	95	90	85
	4	250	270	96	80	68	40
	5	300	311	85	50	40	--
Tube type 5654/6AK5	1	Room	100	100	99	96	90
	2	100	125	100	96	96	90
	3	175	192	100	88	84	71
	4	250	263	100	58	55	32
	5	300	312	55	25	25	--
Tube type 5726/6AL5W (operated as full wave rectifier)	1	Room	95	100	100	100	95
	2	100	112	100	100	100	95
	3	175	180	100	85	85	85
	4	250	253	100	87	70	65
	5	300	301	80	55	46	43

Tube type 6005/6AQ5	1	Room	220	100	97	97	97
	2	100	237	100	95	90	80
	3	175	261	100	65	50	34
	4	250	316	90	30	15	7
	5	500	347	20	3	0	--

The above results have been used to derive curves of percentage survivals against bulb temperature at 250 hours, 500 hours, and 1,000 hours. These curves are given in Figs. 1, 2, and 3 and show quite remarkable changes in survival rate

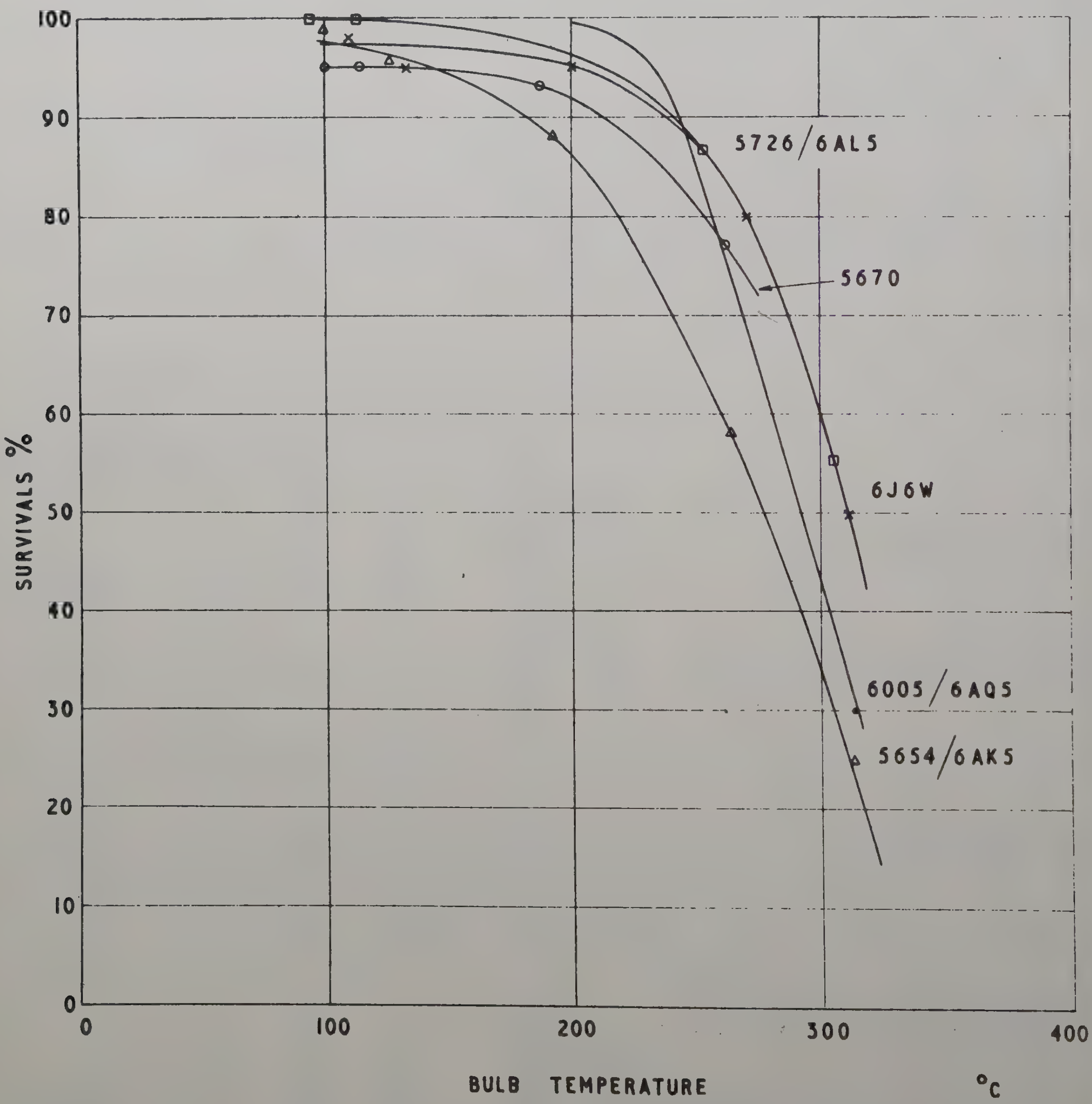

Fig. 1 - Percentage survival vs. bulb temperature after 250 hours life test.

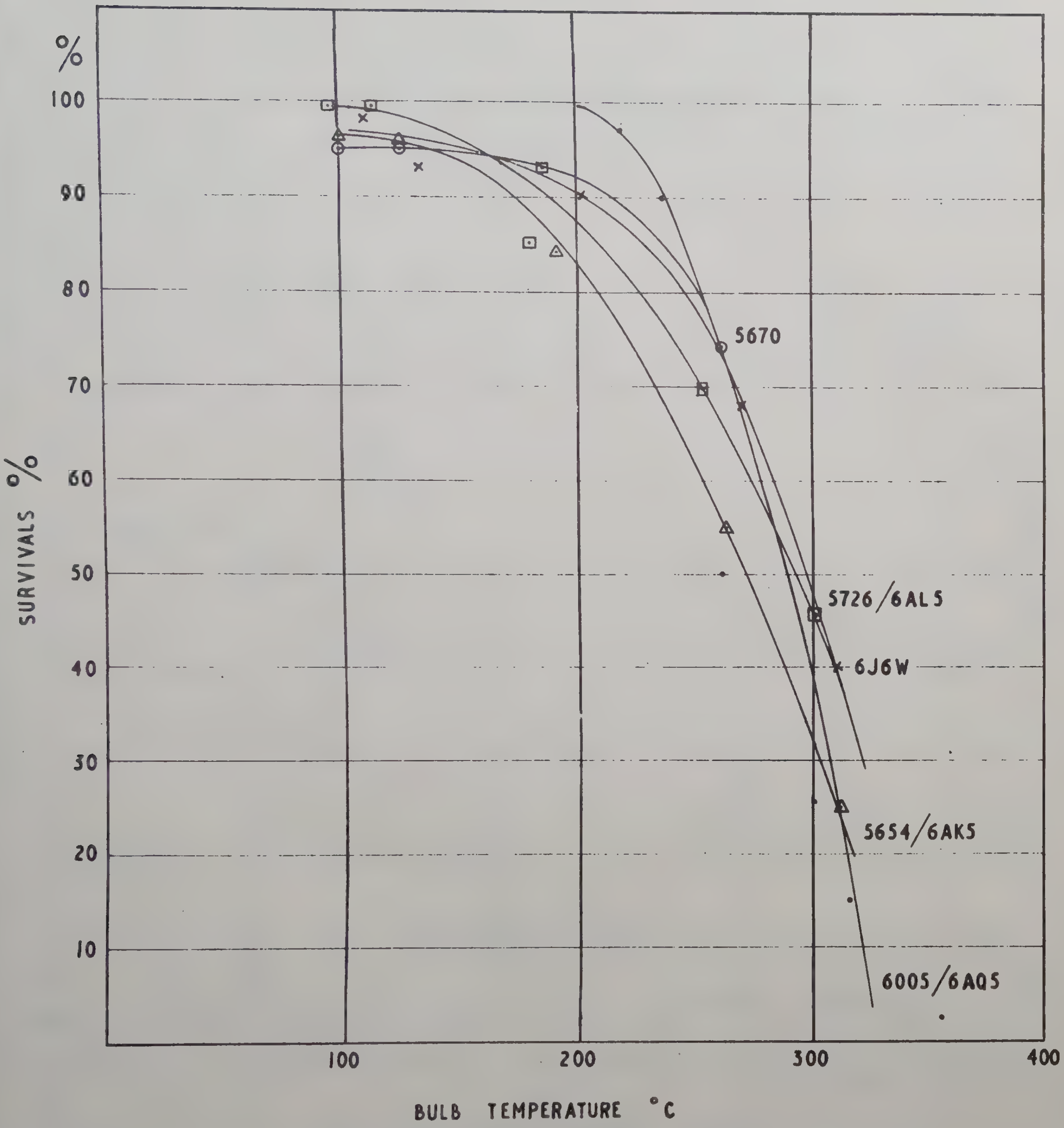

Fig. 2 - Percentage survival vs. bulb temperature after 500 hours life test.

when bulb temperatures exceeding 200°C are recorded. The 6005, which is a "hot" tube, is rather better than the other tubes at 200°C but is significantly worse at temperatures exceeding 250°C.

The curves have been "smoothed" to give a reasonably good fit and a further table of results is given below by recording the average per cent survival for

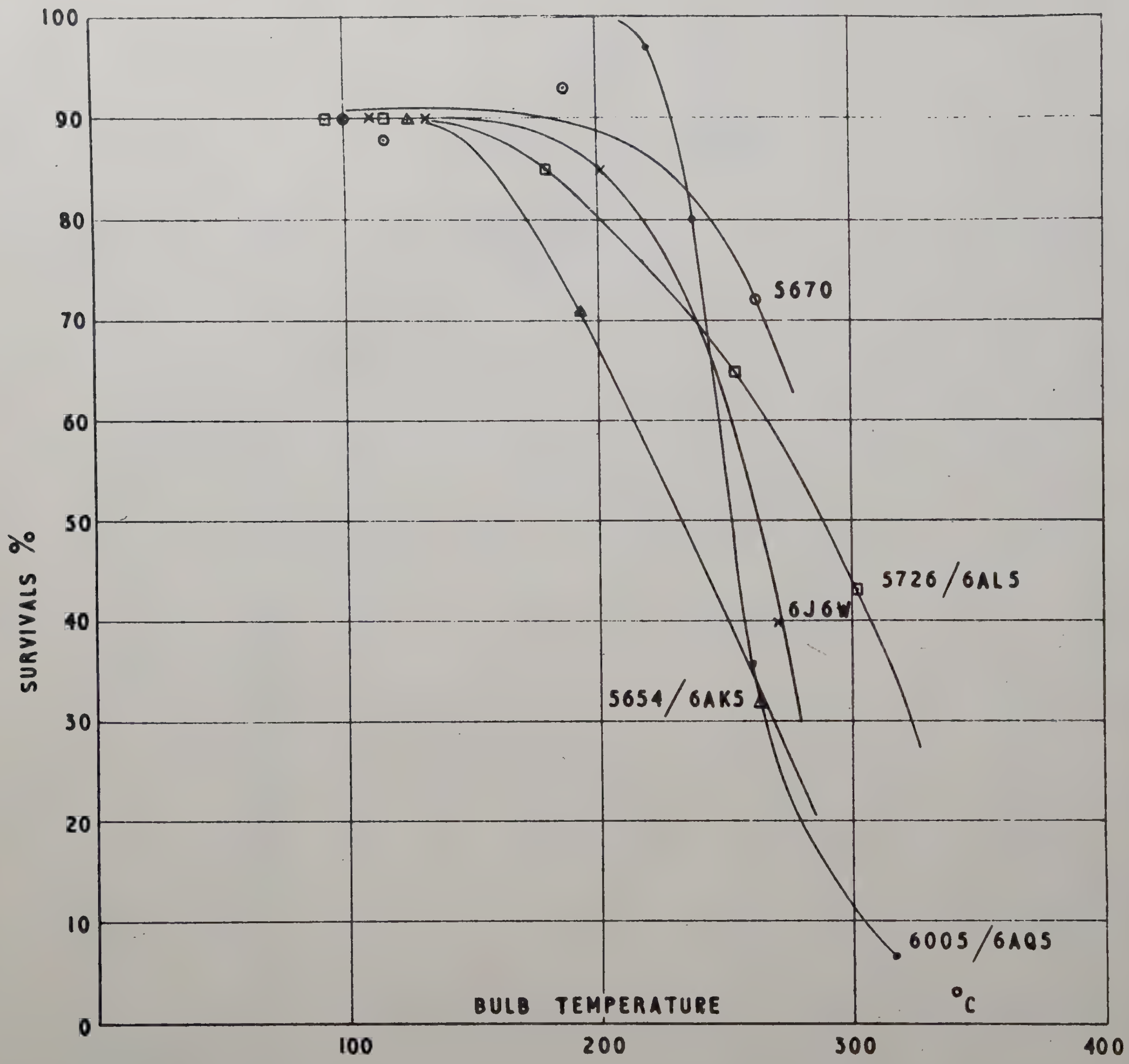

Fig. 3 - Percentage survival vs. bulb temperature after 1,000 hours life test.

all the curves at various bulb temperatures and for the 250, 500, and 1,000 hour life test points. Thus:

Bulb Temp. (°C)	Average Survival Per Cent at 250 Hours	at 500 Hours	at 1,000 Hours
100	97.5	97.5	92
150	97	95	91
200	94	90.5	84
250	81.5	74	60
300	46	39.5	21

These results have been used to derive the curves given in Fig. 4, and it is quite significant that when the results of the original measurements are expressed in this form it is possible to draw straight lines through the recorded points. These are average results for all the five tube types under test, and similar curves drawn for each individual tube type will give different patterns of curves. However, the "average" presentation given in Fig. 4 leaves no doubt that the operation of tubes at bulb temperatures in excess of 200°C will inevitably cause high failure rates.

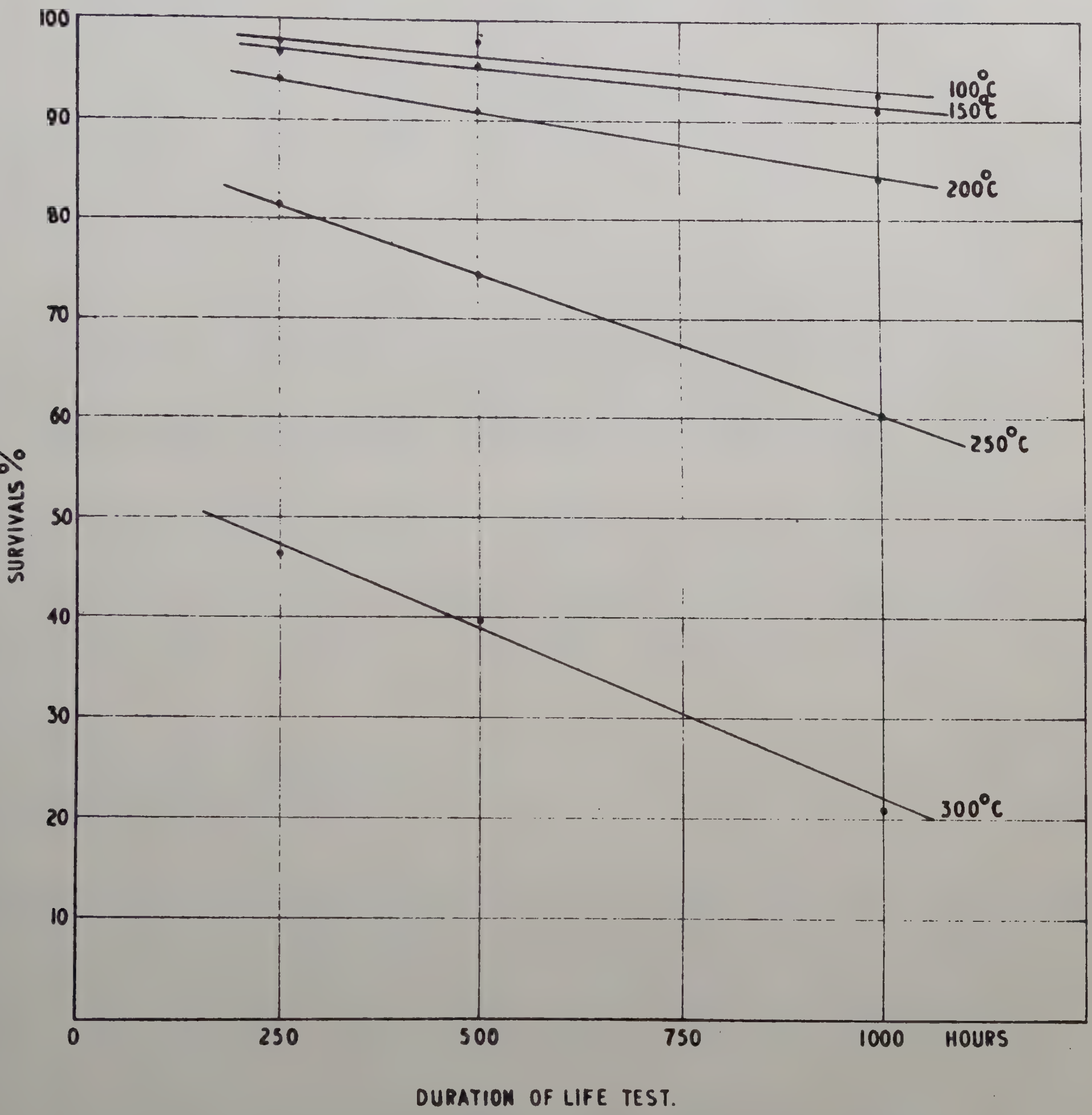

Fig. 4 - Average life test survivals vs. bulb temperature.

It has not been possible to compile the results for life test hours below 250 hours, so that it is not known whether the linear relationships would be maintained from zero hours upwards. If this condition does exist, it would mean that 10 per cent of new tubes would fail on insertion into equipments which cause bulb temperatures of 250°C to be developed. Further, it would be expected that about 40 per cent of tubes would fail on insertion into equipments generating 300°C. Such temperatures are not uncommon.

The above analysis was made in order to try to find possible causes for insertion failures and early life failures in certain equipments which are higher than would be confidently expected, having regard for the known performance of "reliable" valves under specification and life test conditions. These failure rates are not unduly high but are distinctly troublesome, and it would appear that as a result of Mr. Barnett's valuable work a possible lead has been given which may help us to solve this problem. There would appear to be at least three possible lines of action.

1. Reduce the bulb temperature of all valves below 200°C by various heat conducting shields. This may not be possible if high ambient temperatures are being generated.

2. Test all valves for use in "hot" equipments at elevated bulb temperatures and so remove the initial failures.

3. Develop a short range of high temperature valves for use in equipments which cannot be cooled or otherwise treated in some manner to reduce bulb temperatures.

TOMORROW'S QUALITY DEMANDS

Henry O. Imus
East Lynn, Massachusetts

Looking ahead has always been important to the dynamics and growth of American industry. We are all familiar with the early industrialists, famous for their conviction that the American public would accept new ideas and innovations. Such men as Henry Ford and Peter Cooper who looked ahead and guessed right will always be remembered for their contributions.

An accurate estimate of the future is important because it gives us a goal toward which to build. It tells us in which direction to travel. Effort spent in preparing for the future may not yield immediate results or profits, but it will give a better competitive position in times to come. In fact, with the present rapid rate of technological advancement, it may well determine whether or not we remain in business.

Only recently has quality control been considered a separate important function in industry. Although there have always been work checkers on the production line, having no independent authority, they became subject to pressures from production schedules or shop politics. A superintendent, for example, to keep peace might pass on work rejected by the work checker. The foreman, tired of having his work rejected would say, "It may not exactly meet all the drawing specifications, but it will work all right. I know -- I've made them for ten years."

Managers began to realize that quality could not be compromised or bargained away when a close correlation between defect preventive programs and appraisal and failure costs became evident. Quality control concepts began to spread into engineering, manufacturing methods and equipment planning. As the importance of quality control grew as a "trans-function" activity, its accountability and authority became consolidated within one recognized function -- quality control.

INDUSTRIAL PATTERNS

To gain an insight into quality demands of the future we will investigate the intimate relationship between quality control and the product and its manufacture.

First, however, there are several outstanding trends in the evolution of American products and their manufacture that should be examined. Automation in particular has gained widespread recognition. Since much has been written on the technical and social aspects of automation, it will not be considered in detail. It should be mentioned that the ultimate goal of automation in manufacturing is the complete mechanization and integration of material handling, feeding, controlling, and actual production, as well as inspection and test.

An automated production line then becomes more like a system instead of individual machines separated by human beings. If even one operation breaks down this will have on effect that may be felt by the entire system, depending on how closely the system is integrated and what provisions are made for breakdowns.

A fewer number of persons per unit output will be necessary to run an automated factory. The operatives will necessarily be upgraded. They will form a flexible team, ready to handle various factory problems as they arise. Setup, preventative maintenance, and breakdowns will comprise most of their activities. A continuous flow of information will come from all parts of the factory to the central control station. Here central computers will make decisions and process and record information. When a problem arises beyond the capabilities of the computers, an alarm will sound, lights will indicate the location of the trouble, and a team of maintenance and facility engineers will be dispatched to the area. In such a factory, all the planning and designing must be done prior to the purchase and installation of expensive equipment. Never under any system before was the motto "do it right the first time" ever so true.

Automation does not lay claim to the complete future of manufacturing. There will always be those products custom built to individual customer specifications. All products to be mass-produced at some time must be developed on a small volume. There will always be a demand for special items where only one of its kind is built for a particular application.

Increasing complexity and miniaturization is another decided trend today, especially in the defense and original equipment manufacturing industries. Basic scientific advancements in solid state physics, metallurgy, chemistry, and other fields have allowed a substantial decrease in the size of basic components and an increase in the efficiency of many materials. These are used in turn to manufacture more complex devices. At the same time a strong effort is made to keep the size of the over-all equipment to a minimum. The fantastic reduction in size of the basic electronic amplifier component, from an electronic tube to a kernel transistor, represents a ratio of one hundred to one. Many other electronic parts and equipment have undergone a similar transition. Packaging and methods of assembly are making significant contributions to miniaturization. Merely by redesigning the location of the same components and the use of new assembly techniques, such as printed circuit boards, the size of many standard electronic devices have been substantially reduced.

A third trend in modern industry is precision. Precision is a prerequisite for complexity. A simple one-piece product does not need precision. However, as soon as it depends on another part to function, tolerances must be specified for both parts. This tolerance tightens as the number of components increases. Tens of thousandths, microinches, and one hundredths of one per cent are measures increasingly used in industry.

The fourth trend is speed. People are always in a hurry nowadays and the drafting board to shipping time is being squeezed hard. Schedules and dates are paramount because keen competition among manufactured products exists not only in terms of price, but also in terms of time. Time is worth money.

EFFECT ON QUALITY CONTROL

Automation

Test and inspection equipment will be mechanized and mechanically integrated into the production system. This is part of the ultimate over-all automation philosophy as discussed previously. The test and inspection equipment of today

is almost completely manual or only partially mechanized, comparatively far behind production equipment.[1] There is, however, equipment either on the drawing board or in the market that is fully mechanized. Several instrument companies are marketing air gauging systems that can measure dimensions of parts in motion. Another development is an electrical testing board. The electronic assembly to be tested is plugged into the board, test voltages are programmed into the assembly, and the resulting measurements are recorded out. Measurements falling outside tolerances are recorded for analysis and immediate action.

Statistical analysis will be built into the automated inspection equipment. Information obtained by the inspection equipment will be fed back to the machine computer. The computer controls the position of the tool, compensating for tool wear and machine drift. If the normal curve of the output dimensions has merely shifted, then changing the tool position will probably remedy the situation. If the normal curve of the output has instead spread over the limits on both sides, then it probably will be necessary to shut the machine down for maintenance.

Post-production inspection is common today. Automation will emphasize in-production and pre-production inspection.[2] In-production inspection will provide quality information while the part is actually being produced. Although it is impossible to measure the output the very same instant it is being produced, in-production inspection in practice will occur so close in time that corrective action will take place as the variable approaches the limit. High-production automated equipment will demand high-quality incoming material. A faulty part that won't fit a hand-made assembly can be easily discarded by the operator. A faulty part that won't fit an automatically assembled unit will probably jam the machine. Down-time on a highly productive machine is expensive. The elimination of any possible defective machine-jamming material will depend on a tight quality control assurance program. There are two ways to handle this problem: one is to assure the output of previous and contributing equipment and incoming inspection; the other is to automatically inspect just prior to entrance into the machine pre-production inspection.

One hundred per cent inspection will become more widespread. In many cases automated equipment to inspect output 100 per cent will cost only a little more than equipment to inspect 10 per cent. This leads directly into selective assembly. Instead of investing in a large capital equipment to hold down tight tolerances, it might well be more economical to sort the pieces as they are being 100 per cent inspected. When parts are made faster than they can be tested or inspected, a sampling plan would be considered.

The most critical quality control activity will take place prior to actual production. Decisions will be made at that time to fix the level of quality. New design control will be a must in the automated factory as automatic equipment tends not to be flexible. And, also, the investment for equipment will be so great that the cost of making changes in certain design areas will be prohibitive. Many changes which are being made immediately prior to and during production must now be made prior to final design.

Quality-mindedness is applied most where the human factor predominates. In the automated production line the human factor is minimized, and also the importance of quality mindedness. Therefore quality-mindedness must be emphasized with engineering and planning personnel. The personnel dealing with automation

will of necessity have higher qualifications than today's hand assembly factory labor. The operatives will be of a higher skill level. There will be few jobs requiring little skill. Factory labor will be upgraded. Inspectors, as such, just won't exist and in their place will be highly skilled inspection-test equipment setup and maintenance personnel.

Gauge control will play an important role in the automated factory. There must be a continual program to insure that all automated measuring instruments are accurately calibrated. In some instances a particularly critical measuring instrument might have a second back-up instrument to periodically overcheck the original instrument.

Complexity and Miniaturization

As the consumer and military demand more and better performance in a small, compact volume, the complexity of the product and its manufacture increases. Along with increase in complexity goes a growing need for high reliability. Test and inspection equipment becomes more intricate, and there has to be more of it.

Test and inspection planning will be more elaborate. The entire manufacturing organization will seek to become efficient and effective in handling a complex product. The jigs, fixtures, and other equipment used in inspection and test of the more complicated assemblies will necessarily be of a higher level that it is now. The same holds true for the personnel, who must not only be familiar with the intricate inspection and test devices, but also with the product they are testing.

This leads us right into the importance of quality mindedness in a complex and miniaturized product. Although a simple product with a 95 per cent reliability figure might well suffice, when five simple products go together and have to function as one unit, the complex unit is less than 80 per cent reliable.*

The quality level of all the component parts must be increased to a certain level, depending on the application. This will reflect back onto the standards of the quality control organization and to the entire manufacturing and engineering organization. Reliability must be designed into the product, as well as built into the product; quality mindedness must be strongly emphasized in manufacturing and engineering; and component reliability must be maintained at an extremely high level.

There are many more pitfalls in something complex than in something simple. The people working with complexity must be on constant guard and supported with a program of quality mindedness. The quality control methods will be elaborate. The detail of the entire complex must be laid down on paper. Qualified quality control planning and methods men will be breaking out test and inspection work elements, simplifying the operational testing, and inspecting as much as possible. Test and inspection equipment engineers will back up quality control activities with high caliber instruments and equipment. For the more involved equipment a special test and inspection maintenance detail will be necessary.

---

*Assuming all five components are essential to the operation of the composite product and that each individually is 95 per cent reliable, the product rule tells us that the composite reliability is 0.95, or less than 80 per cent.

Precision

With the advent of products demanding and machines capable of producing parts to tolerances in the tens of thousandths and microinches,* the quality control function must make adequate provision to match these tolerances. Quality control has already made good use of optics in the inspection function. Other physical phenomena are being applied to inspection and test. Quality mindedness will play an important part in the manufacture of precision parts. Extreme care will be called for on the part of the operatives to set up and keep the machines in control. A strong gauge control plan will be necessary to maintain the proper standards. Perhaps the factory gauge control plan will be tied into some industrial or national gauge standards system. Cleanliness will be doubly important in the manufacturing and inspection and test areas. A particle of dust can change a physical dimension.

Skilled personnel will be needed in all phases of precision manufacturing, including test and inspection. These persons may not be skilled in the handling of complex product inspection or test (as discussed in the previous section), but they will be required to develop a feeling for small tolerances. They must handle equipment with care and delicacy.

Cycle Time

Even with a tremendous increase in complexity and precision in the products of American industry, our customers are further demanding that we substantially reduce the production cycle time. In an effort to meet this demand the manufacturing and engineering functions have overhauled and quickened their activities. This includes quality control.

New design control now plays a critical function. Not only must it ferret out those problems that might bottle up production of the product, but it must do this in record time. New design control will not be something that a firm would like to do half-heartedly in hopes of picking off the surplus or obvious savings. Instead, it will have a specific, serious responsibility. The persons performing this function can not be dillettantes, but rather experts in the design of this product and the manufacturing capabilities and processes available.

With the time squeeze on all functions, it is well that all quality control objectives, methods, and responsibilities be recognized and integrated well into the pattern of a fast operation. Under the pressure of shortened delivery cycles we have no time for mistakes -- it must be done right the first time.

DEVELOPMENT AND JOB SHOP

In a development and job shop it is important to realize the fact that there exists less "simplified" work that has undergone the analysis of a methods man. As such, each person must have a fuller understanding of the product and the processes involved. With the type of products that are foreseen, we can surmise that it will be of the utmost importance that quality control personnel be of a high caliber, with a desire to build a product that works.

*The Inchworm Motor,[3] manufactured by the Airborne Instruments Laboratory, Mineola, Long Island, New York, controls certain metalworking machines to hold dimensions to plus or minus five microinches.

Methods and sampling plans designed to efficiently handle a large quantity of similar or identical parts are useful in this type of operation only to the extent that large quantities of similar or identical parts are actually manufactured. General approaches and techniques will be developed to handle the various types of parts and assemblies which together form the job shop product.

HOW WILL WE ARRIVE?

Progress in industry is generally of an evolutionary nature. This however does not mean that growth takes place without a good deal of planning and leadership. As the trends of automation, complexity, precision, and short delivery continue to grow, farsighted managers must take positive measures to insure competitiveness through minimal quality costs. In particular, advancement will be made along the lines of quality control equipment, techniques, and methods and personnel.

The large firm is advised to have a group of people devoted to future quality control. These persons might carry on industrial quality control in new equipment evaluation and application. If they intended to actually build inspection equipment they might investigate various physical phenomena, many of which are being applied to modern inspection and test devices. Radioactivity, air pressure, light, magnetics, ultraviolet rays, electronics, chemical techniques, spectrography, X-rays, ultrasonics, interference, and diffraction are but samples of physical phenomena that can be applied to quality control technology. Another activity of advanced quality control will be in the area of new statistical techniques and tools. As A. V. Feigenbaum says, "For too many years we operated by warming over the basic work of Dr. Shewhart and others."[2] New methodology will be required to effect the optimum use of new equipment. Note carefully that "optimum" means complete automation in some applications and virtually no automation or mechanization in other applications.

Although the smaller firm may devote less manpower to this area, it must keep pace with the total industry. As a vendor to a larger firm it will certainly become enmeshed in the quality control philosophy and practices of the larger company. As the field of quality control develops into an integrated activity, the flow of information within itself will tend to transfer new ideas from one firm to the next, and from one industry to another.

TOTAL QUALITY CERTAINTY AT MINIMUM COST

Quality certainty for a minimum cost at the customer level is the responsibility and objective of quality control. "Quality certainty" refers to the quality control activities that will cause the entire plant to produce a quality product. "At the customer level" indicates that quality must be at the level desired by the customer. Excess quality, not desired or paid for by the customer, is uneconomical. Substandard quality is also, needless to say, unprofitable. "For a minimum cost" requires quality control to contribute to profit through minimizing quality costs.

We have seen a preview of the quality control of the future. Automation, complexity, and the other rapidly developing industrial trends will challenge quality control to develop new techniques, new personnel, and new equipment. It is noteworthy that this challenge is not limited to the industries primarily affected by these trends. The concept of reliability, as related to increasing

complexity, demands an exceedingly more dependable product than the old-fashioned component parts manufacture.

BIBLIOGRAPHY

1. "Automation-Continuous Automatic Production." General Electric GEA-6405.

2. Feigenbaum, A. V.: "The new approach to quality control." Factory Management and Maintenance (Mar. 1957).

3. "The Inchworm Motor for Centerless Grinder Control." Airborne Instruments Laboratory, Inc., Mineola, New York.

4. "Automation and Process Control." Section V, Quality Manual, General Electric Manufacturing Services, New York, New York.

5. "Mechanization and Automation in Test." Section II, Quality Manual, General Electric Manufacturing Services, New York, New York.

6. Aller, W. F.: "Built-in Quality Control for Metalworking." The Sheffield Corporation, Dayton, Ohio.

7. Aller, W. F.: "Measure your quality automatically." Automation (Mar. 1957).

8. Bercow and Levy: "Comparative Study of Industrial Quality Control Programs." Massachusetts Institute of Technology, MS B&E Thesis, 1953.

PROGRESS IN TV-RECEIVER RELIABILITY

E. H. Boden
Sylvania Electric Products, Inc.
Radio Tube Division
Emporium, Pennsylvania

In just over ten years, television has grown from an oddity to one of the most common furnishings in the American home. The average householder regards his TV set as an essential appliance almost on a par with his telephone or the pop-up toaster on his breakfast table. We of the electronics industry, associated with the problems of producing this item of standard living room furniture, know that the behind-the-scenes problems have been far from commonplace. Since the early days set reliability, as a dependent function of tube and other component reliability, has been one of the most troublesome problems besetting us. Yet many of us tend to forget the steady growth in component reliability which has taken place in these few years.

Since 1950 the Radio Tube Division of Sylvania Electric Products at Emporium has been conducting life performance tests on Sylvania tubes in various makes and models of television receivers. The year-to-year operation of this life test program has proved most valuable in the maintenance and improvement of tube life performance. Also, valuable information has been supplied to the Radio Tube Division's Application Engineering and Field Engineering Departments concerning the performance of Sylvania tubes in sets of various manufacturers.

During the first few years of the program, various test conditions and procedures were studied to find that combination which would provide the maximum information in a minimum of time. The test conditions, procedures, and data handling methods described here have proved to be the best for the information desired. There has now been sufficient data collected to reveal trends in tube life performance, and an attempt has been made to draw from the results some conclusions concerning both tubes and television receivers. This paper is a report on life test data collected in the last three years resulting from the testing of 15,089 tubes in 1.4 million set-run hours. All data was tested for statistical significance at the .05 level, which means that there is only one chance in twenty that the observed difference does not reflect a true difference.

TEST CONDITIONS AND PROCEDURES

Figure 1 shows a portion of the area being used for set life-testing tubes. Here the sets are run for a period of 1,500 hours, during which time the sets are automatically cycled on 50 minutes and off 10 minutes of each hour, with two additional manual cycles of one hour off during each 24 hour period. Fifteen hundred hours approximates one year of operation. Brightness and contrast controls are adjusted for normal viewing.

A line voltage of 130 volts was selected to produce an accelerated life condition. The degree of acceleration using 130 volts had to be determined from experimental data. For this purpose a representative group of receivers was selected and run for 1,500 hours. Half of the receivers were operated at 130 volts line and half of them were operated at 117 volts line. At the completion of the

Fig. 1 - TV life-test area.

run, sets operating at 130 volts had 2.4 times as many failures as the sets operating at 117 volts. This would seem to say that one year at 130 volts was approximately equivalent to 2.4 years at 117 volts. This same test is repeated each year with current models of receivers to determine if any change might have occurred in this acceleration constant. As yet there has been no significant difference in this constant.

From time to time, television receivers are obtained in groups of ten to twenty sets of each model. One hundred eighty to 250 sets are under test at all times, with upwards of eleven set manufacturers being represented. Each group of receivers is first run 1,500 hours as complemented when received. At the completion of the first run, the receivers are completely retubed and then run for another 1,500 hour period. This is repeated until the sets are replaced by newer models. Each group of sets is used for as few as four runs or as many as seven runs.

When a tube fails during a test run, it is removed from the receiver and a replacement is inserted to serve the set for the remainder of the run. Failure

of the replacement tube is not included in the data but is noted to detect the existence of a critical application in a particular socket. Although important picture tube information and other circuit component data have been obtained, this paper covers only receiving tubes.

All tube failures are carefully studied to determine if any other component failure might have caused the tube to fail. The tubes are visually and electrically analyzed to determine the cause of the failure. A failure is regarded as that level of performance that would cause a set owner to call a serviceman. Records of all tube failures are made on standard McBee Keysort punch cards (KS371N). A sample card is shown in Fig. 2.

By pre-established numerical and direct coding, information concerning failure cause, location, and time is punched on the card. In the same manner, other information identifying the various kinds of receivers is stored. By a simple process called needling, cards representing tube failures are sorted and classified to provide the data desired. In this way expected set survival is calculated and failures are grouped according to causes and location.

Expected set survival is calculated from the tube failures and not from actual set failures. In this way maximum use is made of the acquired data and a more accurate picture of set survival on the basis of tube failures is obtained. The method is best explained by an example. Consider a hypothetical case involving ten sets, where at the end of 200 hours two sets had a horizontal-amplifier tube failure. In this case the calculated set survival would be 80 per cent, or 80 sets out of 100. Now consider the event where at the end of 200 hours one set had a failure of the horizontal-amplifier tube and another set had a damper tube failure. Here the probability that the two events could have occurred in the same set must be considered, and so the expected set survival is 9/10 x 9/10 which equals 81 per cent, or 81 sets out of 100. In the same way, if both the horizontal-amplifier tube and the damper tube had failed in the same set at the end of the 200 hour period, the probability that one of the two failures could have occurred in one of the other nine receivers must be considered. Therefore, the expected set survival is still 81 per cent.

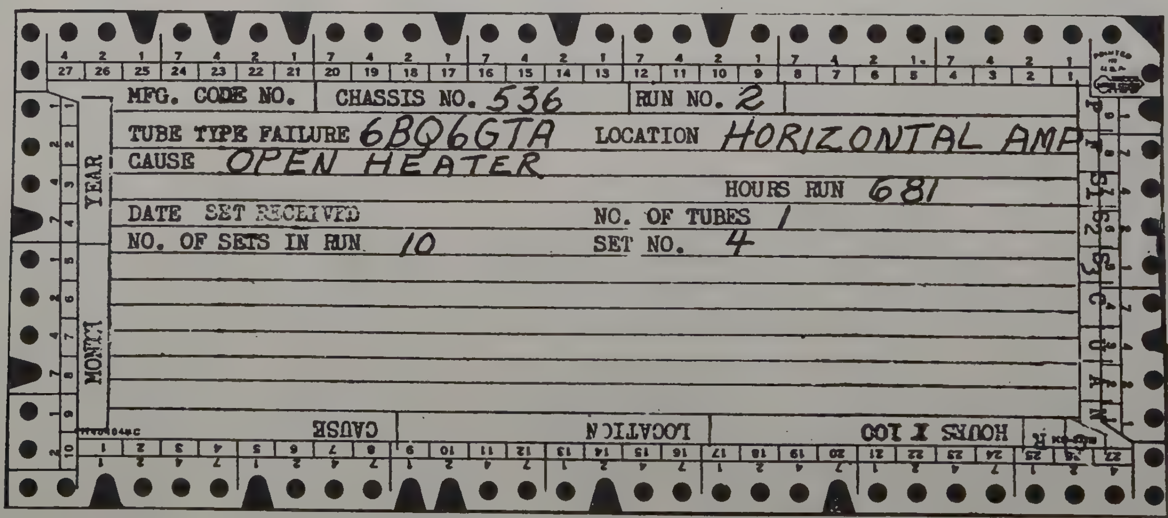
MFG. CODE NO. CHASSIS NO. 536 RUN NO. 2
TUBE TYPE FAILURE 6BQ6GTA LOCATION HORIZONTAL AMP
CAUSE OPEN HEATER
HOURS RUN 681
DATE SET RECEIVED NO. OF TUBES 1
NO. OF SETS IN RUN 10 SET NO. 4
YEAR
MONTH
CAUSE
LOCATION
HOURS X 100

Fig. 2 - Card used to record data.

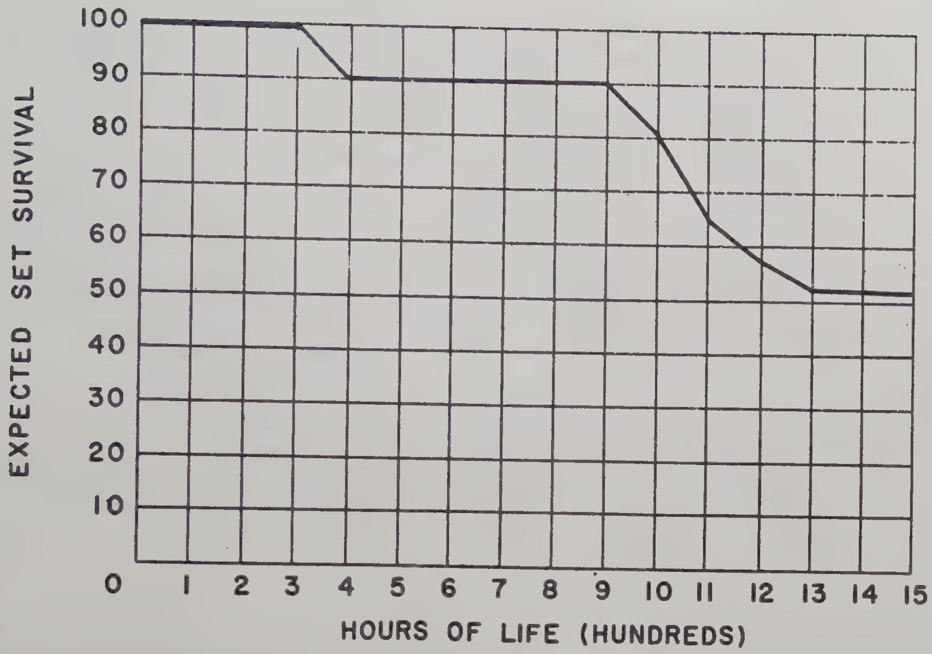

Fig. 3 - Expected number of sets surviving per 100 sets; Sylvania tubes, 10 TV sets, 1st 1,500 hour test.

At the completion of each 1,500 hour run, cards representing tube failures are collected and delivered to the Statistical Engineering Department. Here the tube failure data is analyzed for statistical significance and a report is prepared. An important part of each report is a curve showing expected set survival vs. hours. One such curve is shown in Fig. 3. This curve is computed from the tube failures occurring in ten or more receivers and is a prediction of the number of sets surviving, by hours, with each tube failure regarded as a complete set failure. If 100 sets were run and one tube failed, it is recorded as a complete failure of the set.

Of primary interest to a tube manufacturer is how the tube failure figures have varied in the past three years. The table in Fig. 4 shows the per cent of the tubes which failed from July to July of the years indicated. The differences in the figures shown are significant, and it may be correctly concluded that in the past three years there has been an improvement in television sets and/or tube designs. To remove the "and/or" question, the table in Fig. 5 was prepared. This table represents a compilation of data obtained by using the same group of sets to accumulate failure rates of tubes from three different production years. In this way the variable of receiver changes has been removed and the comparison becomes strictly tubes. In the table obtained it is seen that in 1954-55, 7.7 per cent of the tubes tested in a certain group of receivers failed, while in the following year these same receivers, complemented with tubes manufactured one year later, showed only 6.2 per cent of the tubes tested failing. The 1.5 per cent difference is a significant one and, therefore, it may be concluded that tubes did improve that year. By going further with a second group of receivers, an improvement in tube life performance of 3.4 per cent is noted.

How failure rates vary among sets made by different manufacturers is another very interesting question and is answered by the curves shown in Fig. 6. Illus-

	NO. TUBES TESTED	NO. FAILURES	% FAILED
1954-55	4250	328	7.7
			Δ 1.2
1955-56	5953	387	6.5
			Δ 2.3
1956-57	4886	203	4.2

Fig. 4 - Tubes tested and failures by years.

YEARS TESTED	NO. TUBES TESTED	NO. FAILURES	% FAILED
SAMPLE I			
(12 MODELS —7 MFRS.)			
1954 —55	4250	328	7.7
1955 —56	4309	268	6.2
		DIFFERENCE	1.5
SAMPLE II			
(4 MODELS—4 MFRS.)			
1955 —56	1621	118	7.3
1956—57	1251	49	3.9
		DIFFERENCE	3.4

Fig. 5 - Over-all tube improvement by years.

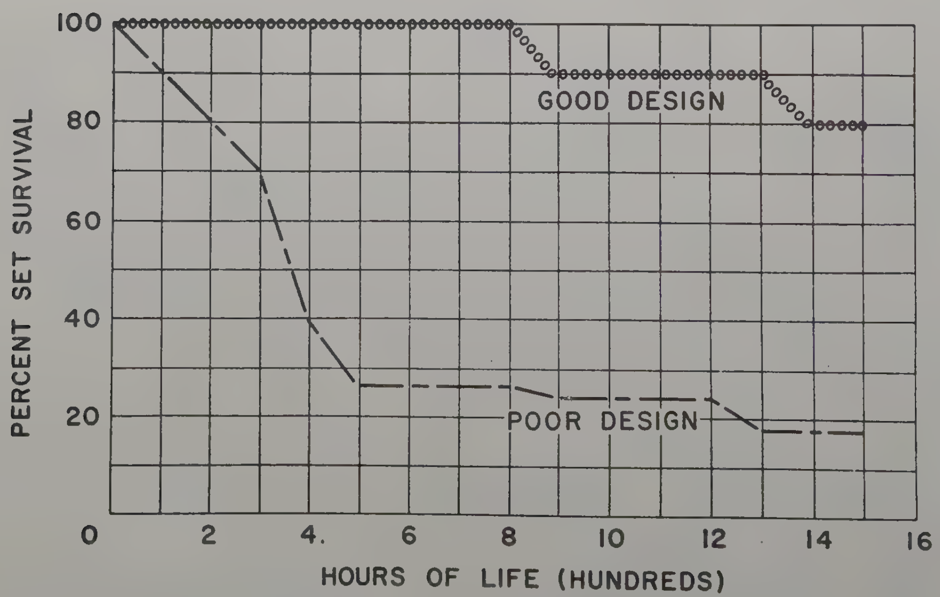

Fig. 6 - Computed set survival of sets manufactured.

trated here are the expected set survival curves for two generally similar sets made by different manufacturers. These curves are consistent with the curves of other years for the same manufacturers and, therefore, are not peculiar to a certain year. It should be noted here that design of some manufacturers' sets have improved, while others have taken the opposite course.

In the past few years, the number of 600 milliampere series-heater receivers has equaled and exceeded the number of transformer-powered receivers. By sorting the cards for series-heater set failures and computing the expected set survival for each of the past three years, the curves shown in Fig. 7 were obtained. It would seem from these curves that there has been no improvement in tubes in the past three years, as was suggested by the table in Fig. 5. However, when the same curve was constructed for transformer-powered receivers, a different result was obtained. As shown in Fig. 8, a four-to-one improvement in expected set survival has resulted in the last three years. The curves shown for the transformer-powered receivers reveals that controls on heater specification brought on by the series-heater sets has also contributed to improved set survival in transformer-powered receivers.

To assist the factory in improving tube survival, tube failures were grouped according to frequency of causes. A list of the most frequent causes is given in

YEAR	NO. OF SETS	NO. SYLVANIA TUBES TESTED	NO. SYLVANIA TUBES FAILED	PERCENT FAILURE
JULY '54-'55	80	1230	59	4.8
JULY '55-'56	92	1438	85	5.9
JULY '56-'57	153	2092	99	4.7

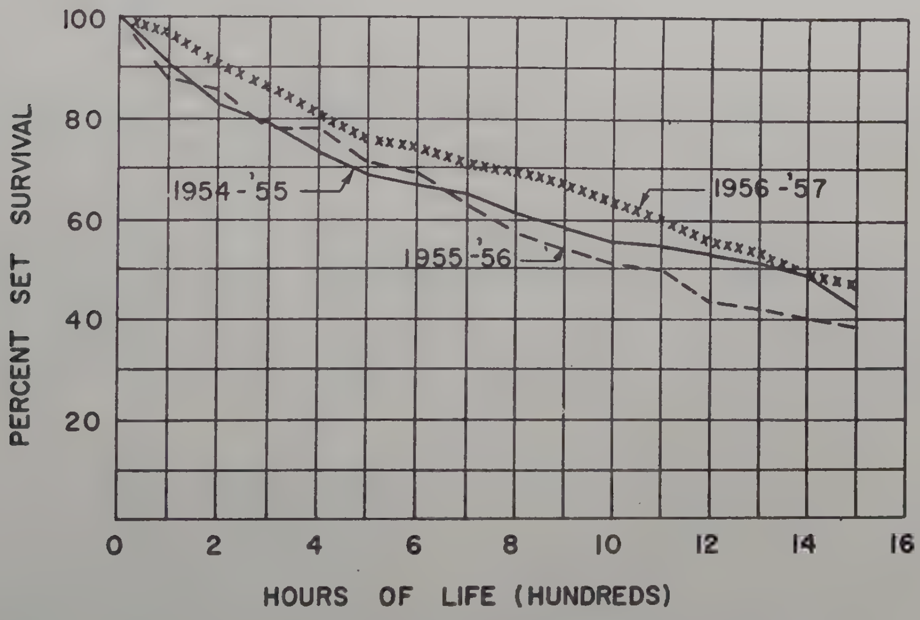

Fig. 7 - Per cent set survival TV sets complemented with Sylvania tubes series-heater string sets (includes series-parallel string category).

YEAR	NO. OF SETS	NO. SYLVANIA TUBES TESTED	NO. SYLVANIA TUBES FAILED	PERCENT FAILURE
JULY '54-'55	120	2300	209	9.1
JULY '55-'56	157	3244	205	6.3
JULY '56-'57	89	1291	58	4.5

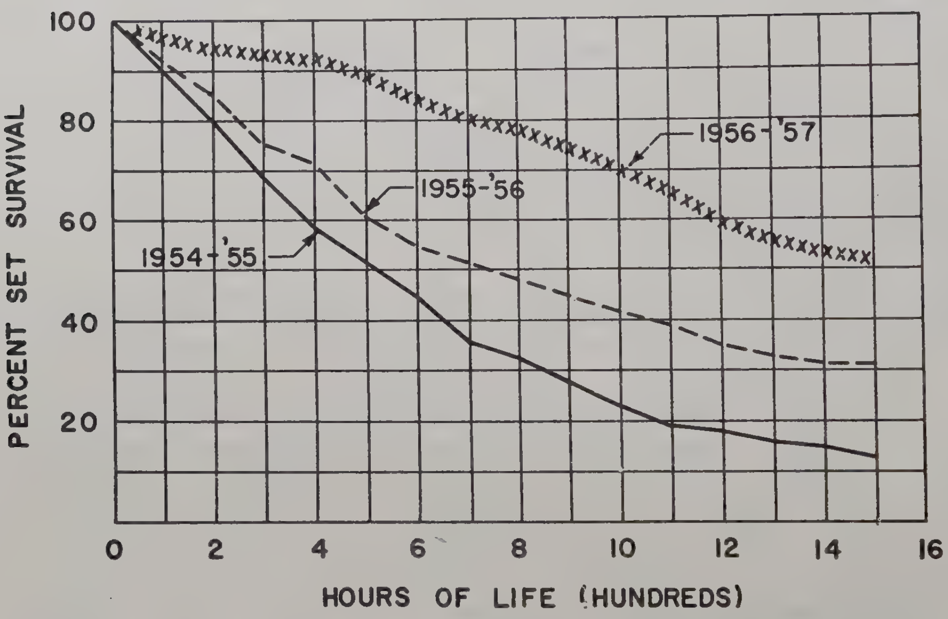

Fig. 8 - Per cent set survival TV sets complemented with Sylvania tubes transformer-powered sets.

Fig. 9. From this table it is seen that of the four major failure causes, per cent failures have been reduced by a factor of three to one, on the average. As of 1957, the big offender is a collection of miscellaneous little items, of which there are some twenty-two.

Another informative table is found in Fig. 10. This table shows those applications with the highest frequency of failures. Because of the severe requirements placed on these tubes, over 65 per cent of all tube failures fell in one of these four locations. However, in spite of the high percentage of failures in these applications, a significant improvement in tube survival has been achieved in all four applications.

At Emporium, Pennsylvania, there are two experimental satellite television stations in operation on Channels 22 and 82. This makes Emporium particularly well suited for the comparison of expected set survival of vhf sets and vhf-uhf sets. As part of the life-test program, a uhf receiver must be capable of satisfactorily receiving off-the-air signals on both Channels 22 and 82. To eliminate as many variables as possible, only vhf-uhf receivers were used for this comparison. The cards were needled to drop out those cards representing tube failures which occurred in sets having uhf. Then, by needling the cards representing failures of the uhf oscillator tubes, expected set survival curves for

FAILURE CAUSE	54-55	55-56	56-57
OPEN HEATER	1.86	1.78	1.02
SHORT CIRCUITS	2.02	1.17	1.19
OPEN WELDS	0.97	0.67	0.23
GAS	1.50	1.51	0.49
OTHER (22 ITEMS)	1.35	1.37	1.20
TOTAL	7.7	6.5	4.2
NO. OF TUBES TESTED	4250	5953	4886

Fig. 9 - Per cent failure of tubes tested by cause.

CIRCUIT	PERCENT TUBE FAILURE BY CIRCUIT		
	JULY '54-'55	JULY '55-'56	JULY '56-'57
HORIZONTAL AMP	25	34	17
VERTICAL AMP	25	29	16
DAMPER	33	17	9
VHF CASCODE AMP	22	18	7

Fig. 10 - Per cent failures of the tubes tested in the circuits listed.

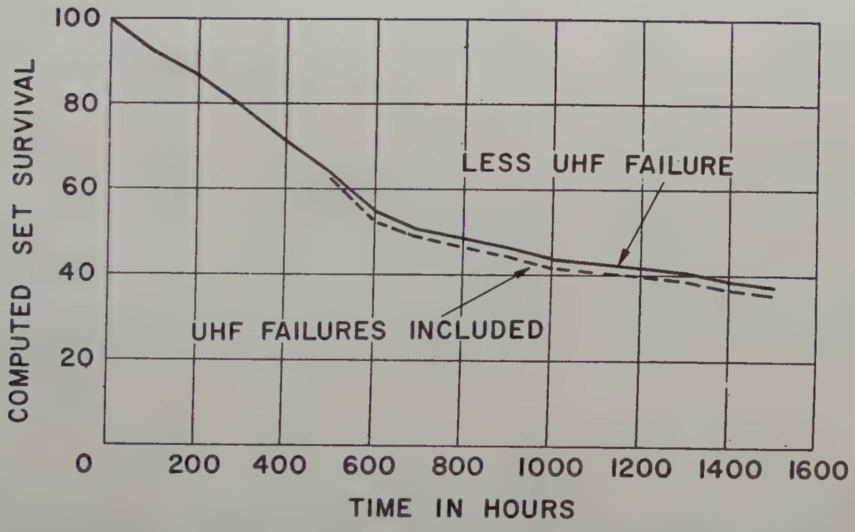

Fig. 11 - Computed set survival of vhf and vhf-uhf receivers.

vhf receivers and vhf-uhf receivers were plotted, as shown in Fig. 11. According to the computed curve, at the end of 1,500 hours there would be 1.2 less receivers surviving because of uhf. Therefore, although there is an additional tube in a receiver with uhf, the expected set survival at 1,500 hours is not significantly degraded by the addition of uhf.

CONCLUSION

The test conditions, procedures, and data processing methods employed in this program have provided a wealth of information from which these conclusions have been drawn.

1. Set survival is dependent on both tube and set design.

2. Sylvania has improved tube survival, which has brought about a significant increase in set survival over the past few years. For further improvement in set survival, improved tube design will have to be supported by improved set design. It is hoped that the information supplied here will encourage equipment manufacturers in the direction of improved set design and thus gain a more favorable acceptance of their products by the consumer.

3. A knowledge of failure causes and locations is a most valuable aid in improving set survival.

4. Receiver life is not significantly affected by the addition of uhf.

These and other conclusions have been drawn from the accumulated data. Because of the flexibility of the above method of information storage, many other conclusions may be drawn with ease and speed.

RELIABILITY CONTROL BASED ON MULTIPLE SEQUENTIAL FEEDBACK

C. M. Ryerson
Radio Corporation of America
Camden, New Jersey

Summary -- The classical approach to reliability improvement is based on a single feedback loop embracing design, development, production, and field service. A procedure of multiple sequential feedback is described which ties in with reliability prediction to provide a specified reliability on the first production run. Techniques are described which can be applied to many industrial operations. Illustrations show how tests and analyses of various kinds fit in.

INTRODUCTION

The classical approach to the production of reliable equipment depends on the use of feedback information from the field to guide redevelopment efforts. Nearly all reliable electronic equipment now in use was developed this way. A design was conceived, manufactured, and put into use. As results from the field revealed weaknesses in the design or construction, this information was collected as a basis for specific corrective measures to be incorporated in subsequent contracts for redesign. The really mature designs now in use are mostly the result of many such cycles of redesign based on the evaluation of field results.

One major weakness of this classical approach is the length of time, often amounting to many years, that is commonly required between the time of the first design and the time that the final perfected equipment is available for general use. Unfortunately, the modern rate of obsolescence is faster than the rate of maturation by this classical approach. A common net result is that many new basic designs are never fully perfected and evaluated for their maximum capability before they become superseded by newer likewise unperfected equipments.

Although steps to improve various phases of the classical approach have been helpful, the need is for general use of a different approach such as is described herein. This new approach, based on multiple sequential feedback instead of the classical single feedback loop, is planned to produce mature designs on each first production run. This paper describes the basic features and weaknesses of the classical approach, reviews efforts that have been made to improve this approach, explains why a new approach is needed, and proposes for general use a multiple feedback approach that is proving successful at RCA.

THE CLASSICAL APPROACH

The classical approach to reliability improvement consists of a single information feedback loop embracing design, development, production, and field service. This is illustrated in Fig. 1. A so-called "good practice" is employed in each of the development and production stages. With the advances which have occurred in the state-of-the-art over the past years, the requirements for what constitutes good practice in each technical area have changed. The main approach, however, has generally remained the same since the earliest days of engineering.

The field information obtained after each redevelopment cycle serves to trigger a limited number of the more obvious and less expensive corrective meas-

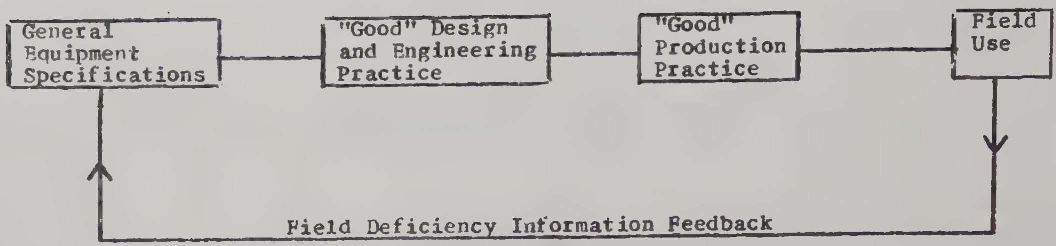

Fig. 1 - The classical approach to reliable equipment.

ures to be taken during the next redesign cycles. These measures are evaluated in turn for their effectiveness during subsequent field use. Many total redesign cycles are sometimes necessary for the complete evaluation of many important design variables. This process is slow and many desirable corrective measures are never taken because of the cost and delay associated with a complete redesign cycle or because evidence does not seem to warrant it.

During the early days of radio so little was known about most of the electronic circuits and parts that the state-of-the-art and the related techniques which could be considered as good practice were at a very low technical level. At the start of this new electronics industry nearly all of the development work could be classified as cut-and-try. As the knowledge of physics and materials advanced, techniques were devised which elevated the level of good practice. New theories and design guides culminated in handbooks and engineering tables which have themselves been modernized and improved many times. This has been the pattern to this day, and in many places the accepted procedure is still one of engineering to specifications from handbooks, then manufacturing, and finally field testing in order to evaluate the design. Good and reliable equipment can still be produced by this method if you can afford the time and money. Unfortunately, however, the state-of-the-art has been accelerating so rapidly that now many basic designs become obsolete in their function before they can traverse the necessary number of redesign cycles required for their perfection.

This problem of obsolescence before maturity has now become serious because of the current rate of technological advance. New requirements come into effect faster than designs can be perfected to meet the old requirements. A brief historical review of some major technical events may serve to illustrate the fast upward rate of change of the state-of-the-art.

It is sometimes hard to realize that it was only a little over a hundred years ago that military cannon were cast of iron or bronze and bolted solidly to wooden carriages. Night illumination at that time was largely a matter of open flames. Just fifty years ago the best cannon had become steel rifles but were dependent on gears and cams for manually cranking the barrel into position. Electricity was only beginning to be used for general lighting, and wireless communication was only a laboratory novelty. The first airplane flights were not made until 1903, and it wasn't until near the end of World War I that the first aerial dogfights occurred using pistols and hand-held rifles as armament. It was only about twenty-five years ago that a few simple radios first began to appear in airplanes.

Since that time technological advance has occurred at an ever increasing rate. Today there are artificial satellites circling the earth with automatic telemetering. Tomorrow we might see a manned fort in the sky, and the next day

a completely automatic space station. Such fantastic developments are no longer idle fantasies but have become practical engineering problems. Indeed, the limit to the extremes that technical complexity and automation can go is fixed by the reliability that can be achieved in the designs.

The rate of technical progress has been "snowballing," but the rate at which industry can produce mature designs has not kept pace. The deficiency is in the classical approach to product improvement. The need is for improved means of obtaining mature designs at a much faster rate.

AN INTERMEDIATE IMPROVED APPROACH

An improvement in the classical approach is illustrated in Fig. 2. There is much work being done toward developing better specifications, better engineering and design practices, and better production techniques. The latter includes the general use of statistical quality control in the factory. Improved field conditions, better operator and maintenance training, and elaborate automatic tabulations of field failure data are steps being taken to improve the classical approach. The emphasis is on getting better data faster so that the redesign cycle can be shortened. Major efforts are also under way to improve engineering so that the available parts will be better and so that designs will make better use

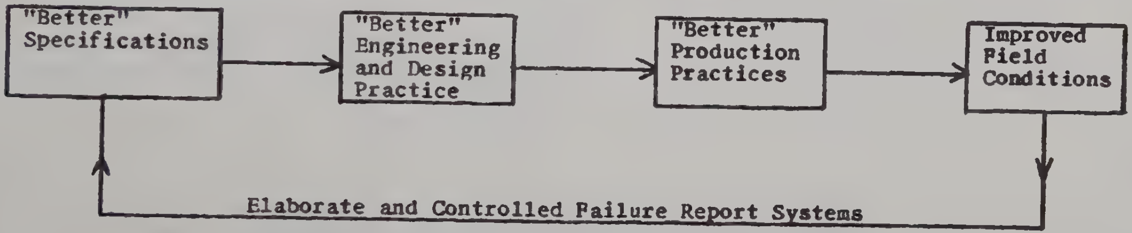

Fig. 2 - An improved approach.

of the parts. Techniques are being devised to ensure that circuits will have greater safety factors and be more tolerant of parameter changes. Emphasis is being placed on ease of maintenance, better maintainability, marginal testing, and other improved field techniques.

These efforts are good and are helping produce better equipment, but they are not enough. This improved classical approach still requires field evaluation of each design and each design change, and this is not a good enough technique to raise the equipment maturity rate to the level of the modern obsolescence rate. A new approach to the fast development of mature designs is needed. Such an approach is available and has been proven practical by RCA; it is called the multiple sequential feedback approach.

MULTIPLE SEQUENTIAL FEEDBACK

In brief, the multiple sequential feedback approach replaces many full redesign cycles by multiple prediction of the probable results of many tentative design changes. Analysis and prediction based on design consultation and statistical techniques enables the equivalent of many redesign loops to be performed rapidly on paper. When this process yields a design that can be predicted to have the highest possible field success, the design is frozen. Subsequent special quality control loops prevent the manufacturing cycle from degrading the

potential reliability inherent in the design, and a final product evaluation phase following production establishes the success of the whole multiple control process before the product is released for use.

In place of the single feedback loop characteristic of the classical approach, the multiple sequential feedback approach employs six major control loops and many secondary control loops within these. This approach is illustrated in Fig. 3. Each control loop consists of feedback from specific analyses which determine the progress of each project from one stage of development or manufacture to the next. The first information feedback from the field is thus only a check on the effectiveness of the many anticipatory corrective measures which have been previously taken during the various stages of design and manufacture.

The various control loops function by putting emphasis on obtaining adequate information in the correct form at the right time for each management decision on each project. Thus the reliability program on each project is continually changing to meet the specific needs of the project as it progresses. In general, specific assignments in key areas of each operation are made to reliability representatives. These people are required to obtain a certain type of information and make it available on time for use by the regular line operation. This might be called control by education and analytical review. The responsibility for action remains with the regular line management. The permanent record of their achievement in producing a reliable product reveals their compliance with the program. Certain specific objectives differentiate the functions of the various control loops. The following sections summarize them.

Contract Control

Successful operation of reliability contract control results in contracts which contain specific and realistic over-all equipment or system reliability goals. The cost of achieving these reliability goals must be recognized in the

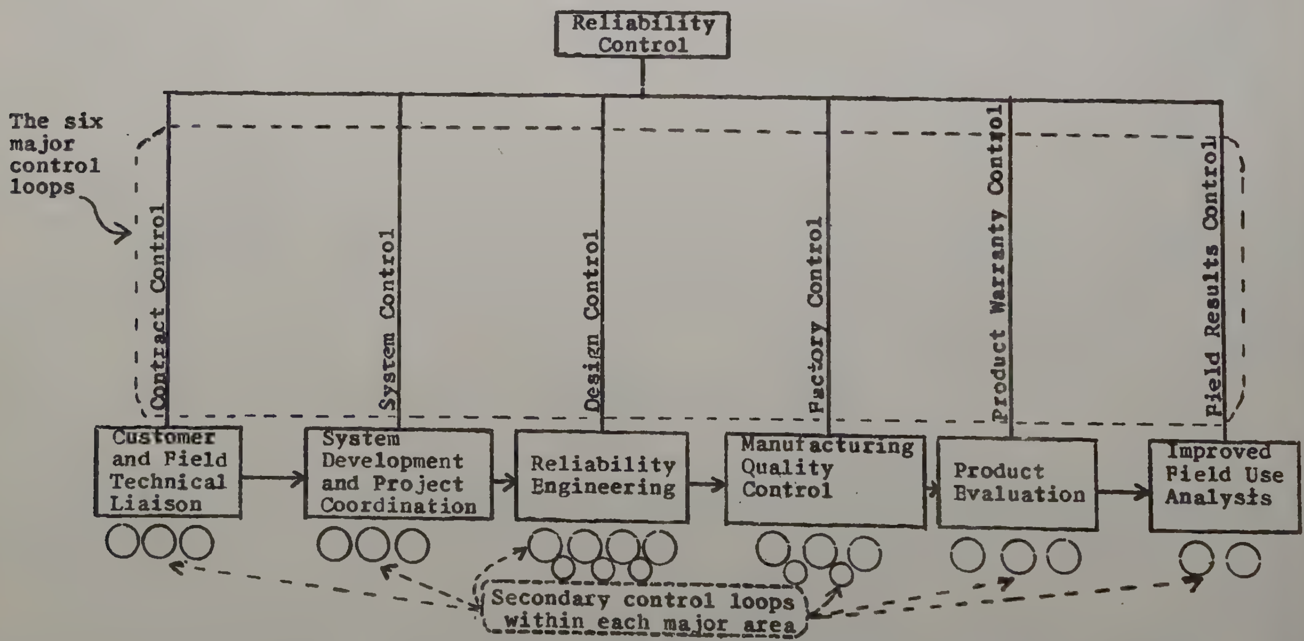

Fig. 3 - The multiple sequential feedback approach.

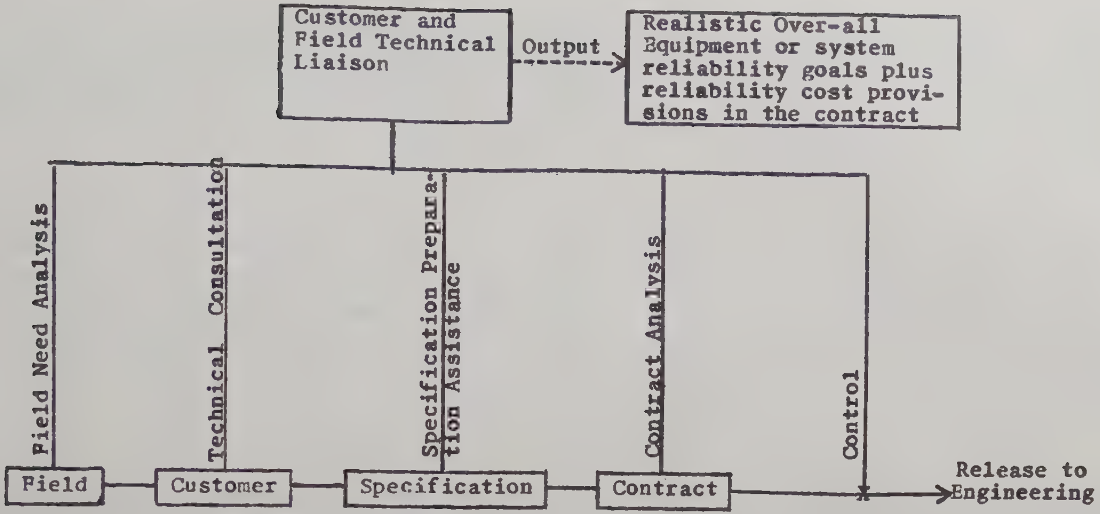

Fig. 4 - Contract control.

contract and provision made for direct reliability charges. The factors involved in achieving this result can be summarized as follows (see Fig. 4):

1. Field need analysis
2. Customer technical liaison
3. Specification preparation assistance
4. Preliminary reliability analyses and comparison with other projects
5. Interpretation of contract terms
6. Concise summary of project objectives
7. Analysis of unique or critical contract requirements
8. Digest of applicable mil. specs
9. Emphasis on criteria for acceptable performance
10. Review of unusual or critical conditions
11. Arrangements for engineering liaison with appropriate customer contacts
12. Formal release of project to engineering with clear-cut program requirements.

System Control

The system control operation results in clarification of all reliability goals as they apply to systems, equipments, and components. Specific objectives for reliability achievement are developed and furnished to the design groups along with their other design criteria such as function, embodiment, cost, etc. These reliability goals must be realistic and possible to achieve. A first report to the customer should explain how these goals were developed and how they will result in an end product which meets the field need and the contractual obligations. Probable difficulties in the path of achieving these goals should be explained so that the customer will be aware of the validity of his expectations.

Sometimes a project may consist of a redesign of an existing equipment which must be reproduced in new form or size to perform the same functions but in a more severe environment. Since the same electrical functions are involved, the original circuit can serve as the basis for setting the new reliability goals. Suppose, for example, that the project is to subminiaturize a 1,000 part equipment to fit a smaller space and to operate at a higher local ambient air tem-

perature. Suppose also that the original equipment performed with a 200 hour mean life at 40°C and that the new version should have about 500 hour mean life at 80°C. From Fig. 5 it can be seen that the equipment of 1,000 parts with a mean life of 200 hours is operating at about the S level of .5 per cent per thousand hours average failure rate for the parts.

This failure rate is not too difficult to achieve at 40°C. The new requirement is quite different, however. To make the new equipment as good as a 500 hour mean life requires (from Fig. 5) an average part failure rate of about .15 per cent per thousand hours. It is presently impossible to buy many types of parts which the part suppliers will certify to this level at 80°C. Thus, such a project will require many special reliability screening tests and involve many difficult vendor and procurement problems.

In order to clarify how severe the new procurement will be, a part count of each type can be made from the old equipment. This count may show, for example, that the major procurement problems will be in relays and tubes; resistors, capacitors, etc., may be available to meet their required failure rates. The gathering of this information and the reporting of it to the customer is an important part of the system control. It keeps the customer informed of the state-of-the-art and how his project fits into it. This effort also guides all subsequent engineering efforts by revealing the areas needing the most attention.

If the process of setting part goals to meet the customer request shows that the project is impractical and doomed to failure because of impossible failure rates being required, the customer should know this at an early hour before money is wasted in development. Perhaps the requirements could be lowered in such

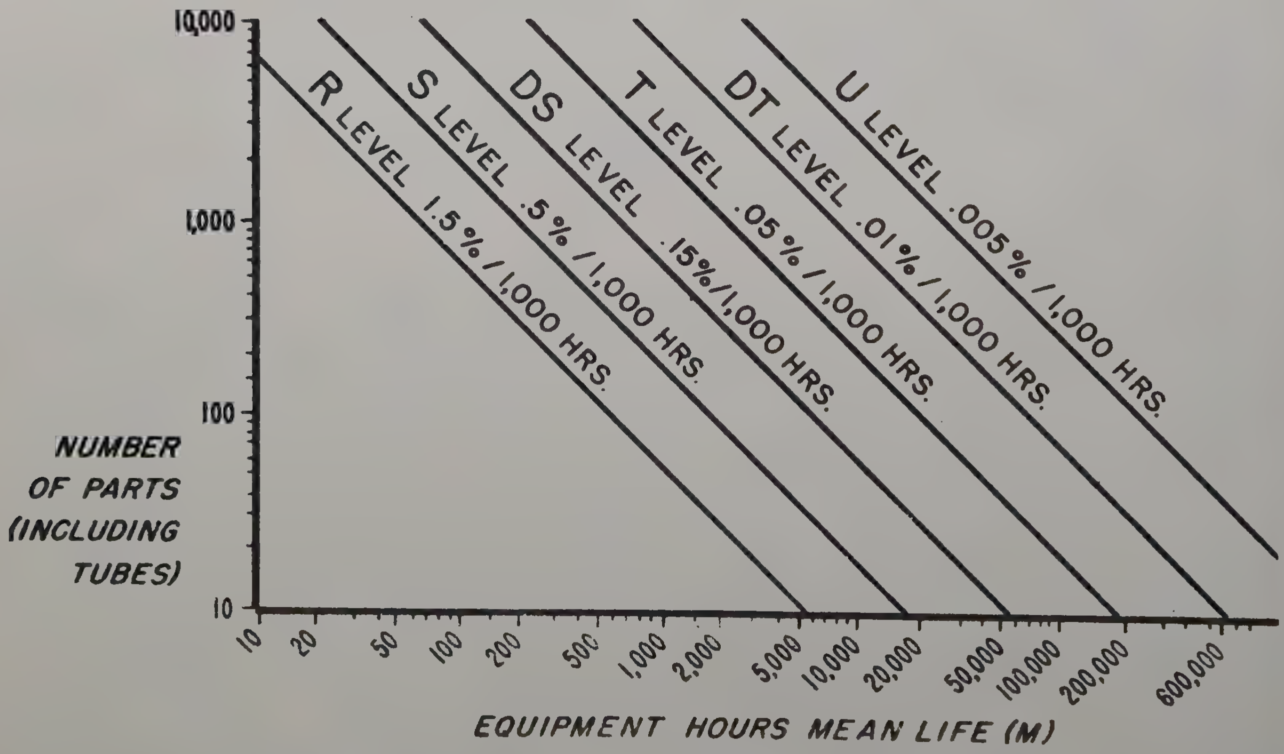

Fig. 5 - Equipment reliability vs. design level.

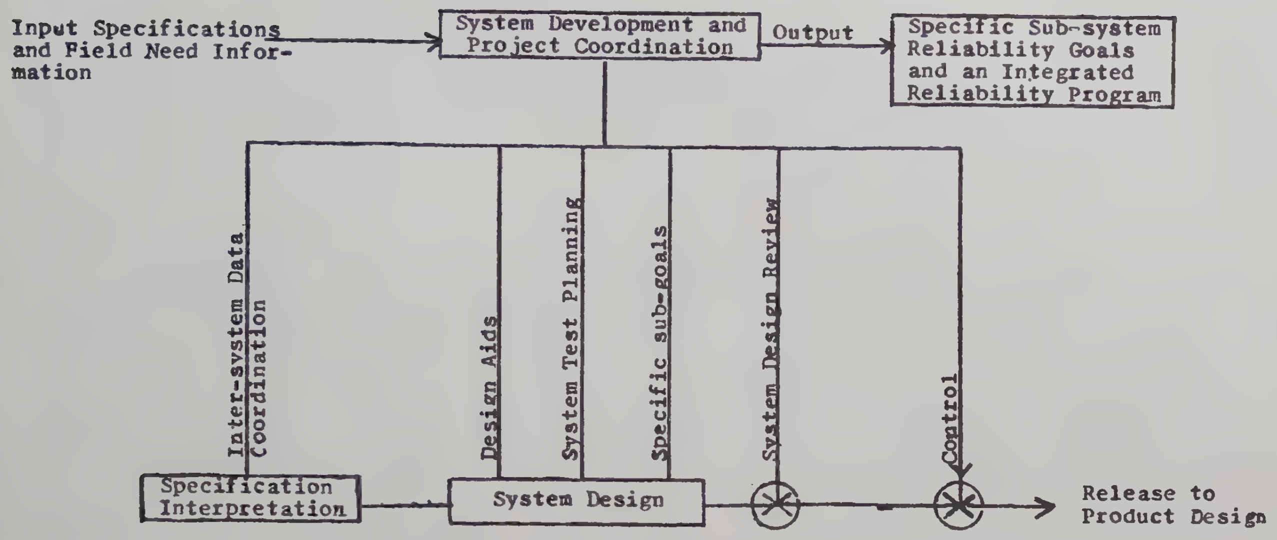

Fig. 6 - Reliability system control.

cases or provisions made for supplying cooled air to the equipment. Also, such information may lead to direct projects for specific part improvement.

The factors related to system control can be summarized to include the following (see Fig. 6):

1. Reliability data compilation and comparison of similar systems.

2. Analysis of project specification compatability with the field need.

3. Prediction of ease of probable achievement of reliability goals based on part counts and failure rate information on available parts.

4. Detailed system design to include specific subsystem reliability goals and specifications.

5. Design aid development and summary for assisting in achieving the reliability goals.

6. Plans for system and subsystem testing including acceptance criteria, test conditions, and facilities assignment.

7. Independent system design review that assesses reliability specifications and compliance with system design objectives.

8. Plan of complete reliability program plus completion schedule.

9. Complete system assembly and test coordination plan with specific instructions to product designers.

Design Control

Design control is maintained successfully by means of an organized reliability engineering operation. Coordinators are assigned to each project and their

full-time direction is handled by a reliability administrator on the chief engineer's staff in each product line or department. Standards and part application groups are established and full liaison is maintained with a central reliability and standards activity. Formal review teams and programs are established to evaluate alternative designs, and formal use is made of three types of reliability prediction.

Design reviews, an important part of design control, are performed by a team of mature engineers who have had experience in the particular type of design under review. They are appointed by a review supervisor on each project to serve only as long as the need for their specialized experience exists. The purpose of the reviews is to focus the thinking of many experienced designers on each design problem so that the final design will reflect a concerted opinion toward mature design. Alternate designs for equivalent function are thus screened for the optimum compromise of engineering criteria. As each designer completes his assignment he lists his design with the review supervisor. Copies of the circuitry

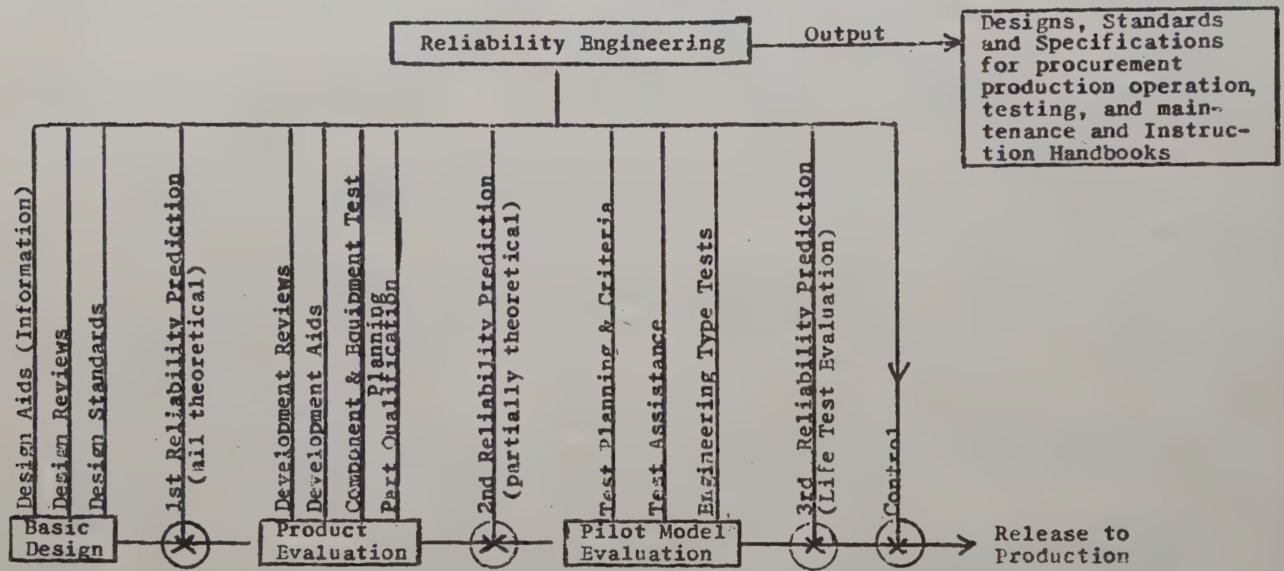

Fig. 7 - Design control.

and related analyses material from the engineers' notebook are distributed in advance to those invited to participate on the review team.

At the review meeting the designer explains his design in greater detail and obtains the collective advice of those present. Most designs may benefit from many reviews before the design is frozen for inclusion in the project design. The three basic bypes of design review are preliminary, progress, and final. The preliminary reviews analyze a tentative proposal and survey possible alternatives; the progress reviews examine the design status and audit the theoretical and analytical justification for each design decision; and the final reviews confirm the validity of the design approach and approve the compatability of individual designs with the over-all project objectives.

Three types of reliability prediction are used in addition to the design reviews to control the progress of the design project within engineering. The first type is performed as soon as a circuit or subsystem design has been tenta-

tively established on paper. This first prediction is entirely theoretical, since no hardware has been produced except perhaps a few breadboards. The circuit design itself is analyzed for the probable stress that will be placed on each part and the probable immediate environment of each part. From this information the most likely failure rate of each part is deduced and summed to predict the inherent reliability of the design. Special rating charts have been designed for this purpose. If this first reliability prediction for each subsystem meets the goal set for it during the system design, approval is granted to freeze the design at this point and to proceed with the development of engineering pilot models. Redesign and design reviews are repeated until this first reliability prediction meets the assigned goal on each circuit and subsystem.

The second stage of prediction is performed on accumulated circuits as soon as hardware similar to the final model is available. This should roughly simulate the general configuration and embodiment of the final equipment. Actual measurements of environmental conditions are used to interpret new analyses of part loading and to establish a second prediction of inherent reliability. When this figure checks with the first prediction and meets the assigned goals, then approval is granted to manufacture the engineering prototypes. Since this analysis considers each part in each circuit, a comparison of this data with the data from the first prediction will quickly identify those areas needing additional development or redesign. These two analyses likewise provide the information in regard to the required part failure rates for use in the preparation of part procurement specifications.

Unlike the first prediction which was entirely theoretical and the second which was partially so, the third prediction is not theoretical at all but consists of special reliability tests run on complete engineering prototypes. Statistical data are obtained on actual failures which must correlate both with predictions 1 and 2 and also with the original system goals. Again high failure rate areas which show up under design or the use of improper parts are quickly located by comparison of the test data with the previous prediction figures. When the results of prediction 3 correlate with the previous two predictions, and actual failure rates comply with the initial goals, it is safe to release the design for production.

Engineering reliability is also responsible for qualifying the parts specified in the design. The major portion of this responsibility is to ascertain that the parts specified will exhibit an acceptably low constant failure rate for a suitable period when they are stressed to the conditions involved in the design. Or in other words, engineering qualification must certify that the sample parts obey the exponential failure law and have an acceptable failure rate for a suitable time when used in the planned application conditions.

Factory Reliability Control

Factory reliability control is maintained by means of an organized quality control operation. Although quality control can do nothing to improve the reliability of the product above that inherent in the engineering design, it has the major responsibility of insuring that the manufacturing operation does not degrade the reliability below the inherent potential of the design. The most mature design, accompanied by the best part specifications cannot result in a reliable equipment unless the manufacturing operation brings out the maximum po-

tential of the engineering work. Quality control must insure that the various reliability goals established during the design operation are met during the factory phase.

It was mentioned earlier that engineering must qualify the parts specified to have a suitable life characteristic. Often the parts which receive engineering qualification have been hand-made in the supplier's model shop. Quality control must insure that subsequent production lots of parts retain the same life characteristics and low failure rates. For very reliable complex equipment the problem of procuring parts to a known suitable low failure rate is very difficult. Special incoming screening operations and elaborate acceptance tests which determine the time stability of the incoming parts must be planned and maintained. A thorough study of the mechanism of failure and the design of special tests based on these findings are major responsibilities of quality control.

There are essentially five control loops in the factory reliability control operation: part and component procurement, acceptance testing and incoming inspection, materials handling, production inspection, and production type-tests of equipment. These loops and related factors for reliability control can be summarized, as shown in Fig. 8. Equally important from the long-range viewpoint, but not shown in Fig. 8, is the responsibility for all those concerned in the vendor coordination program and parts procurement to pass the burden of making and supplying certified better parts back to the part manufacturer.

Product Evaluation Control

Product evaluation control provides for a thorough reliability evaluation of all equipment following production and prior to shipping. Special reliability

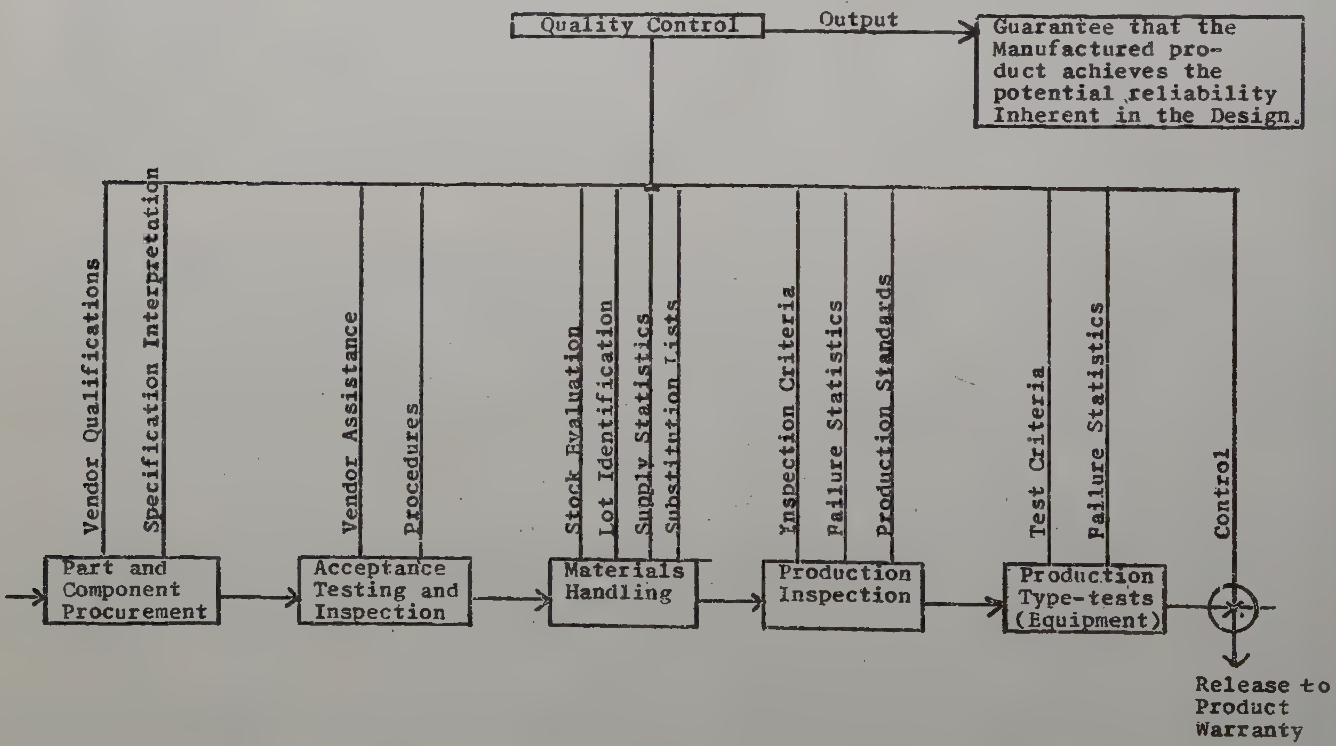

Fig. 8 - Factory reliability control.

tests under controlled conditions yield an accurate measure of the inherent reliability of the product. This measured figure constitutes a fourth prediction which must compare favorably with the first three if quality control has succeeded in its mission. It is important, therefore, that an independent, unbiased group perform this control operation.

If the actual failure rates as measured on final production equipment (while these are undergoing simulated field tests) do not coincide with the earlier predictions, a comparison of the tabulated facts for each circuit both before and after manufacture will reveal the areas needing better factory control or the use

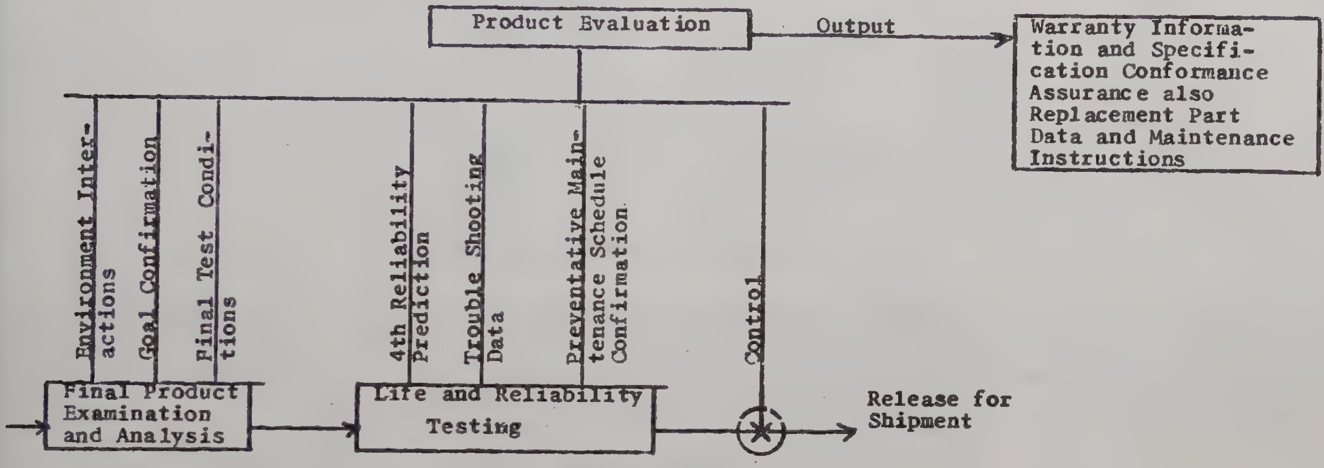

Fig. 9 - Product evaluation control.

of better parts. When all four predictions coincide with the contract and system goals, there can be considerable confidence that the equipment development has approached maturity on the first production run.

The factors related to the product evaluation control are illustrated in Fig. 9. It can be seen that the very important outputs of this control loop are warranty information for the product, assurance of specification and contract conformance, and confirmation of part failure rates. The portion of the instruction book on trouble shooting should be written to take advantage of the experience gained during this operation. Preventive maintenance schedules should also be verified by the results of this control phase or modified accordingly. Repeated product evaluation tests will assure a uniformly reliable product.

Field Results Control

Earlier sections described the objective of this multiple sequential feedback approach to be the obtaining of mature designs on each first production run. If this objective is successfully achieved on a given project, field results can only confirm the success. Negative confirmation from field results may reveal valuable information about the effective maintainability of the design, the operation or maintenance ability of the field crews, weaknesses in the contract specification or evaluation tests conditions, and misapplication of the equipment. Many uncontrolled parameters in field applications can introduce a variety of conflicting evidence into the records of field results.

The effective program for field results control will establish analytical and statistical measures for categorizing and evaluating each of the contributing

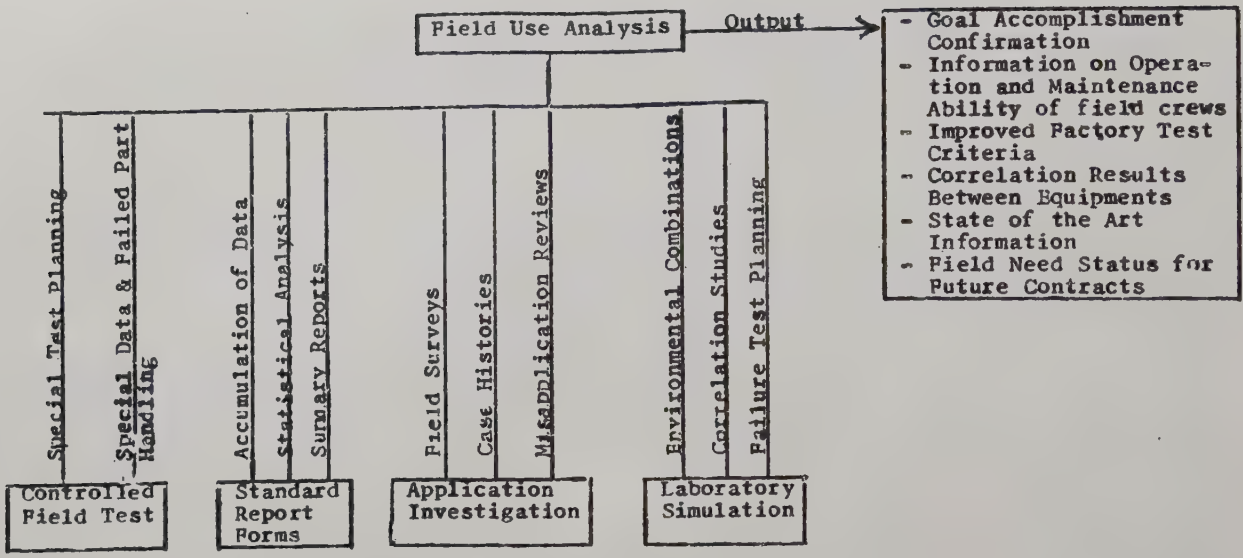

Fig. 10 - Field results control.

factors. In addition to the information obtained about the field application conditions and the state-of-the-art in the field, each project can certainly provide information helpful to other future projects. Many of the factors involved in this sixth major control loop are illustrated in Fig. 10.

CONCLUSION

Most attempts to improve the classical approach to more reliable equipment fail to consider the major weakness of the single long-time loop. Since the essence of meeting the modern need is speed of design maturity, an entirely new approach such as described herein is needed.

The multiple sequential feedback approach establishes new criteria for, and new concepts of good practice in all development and production specialty fields. Statistical analyses and multiple predictions, as well as formal reviews by groups of experienced specialists, reveal the best engineering compromises and the best production practices. The age of cut-and-try has given way to the age of formal analysis and prediction. Completely new standards are necessary and available for modern good engineering and good production practice.

STUDENTS: ATTENTION

DR. WILLIAM G. TULLER MEMORIAL AWARD

Awards of $250 will be made for the best papers submitted by a senior or graduate student on the subject of component parts. The subject may relate to operational theory, materials, construction, design, testing or application of any electronic component. Papers must be submitted by December 31, 1958. Consult the Office of the Dean or your IRE Faculty Advisor for additional information or write to:

Leon Podolsky, Chairman
Awards Committee
IRE Professional Group on Component Parts
Sprague Electric Company
North Adams, Massachusetts